# USE OF LAYERED THEORY IN THE DESIGN AND EVALUATION OF PAVEMENT SYSTEMS

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16. Abstract

This report presents a description of layered elastic analysis and describes five computer programs which solve the necessary differential equations. These programs are CHEV5L, CHEV5L with iteration, BISAR, ELSYM5 and PSAD2A. Uses are suggested for each program according to its most practical application and a comparison is made between the methods based on the same input data set.

Supplementary information has been included concerning resilient modulus properties of common pavement structural materials and the operation of all computer programs on the Boeing Computer System.

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# FOREWARD

A number of computerized "tools" have recently become available which can aid the engineer in designing better roads. The intent of this report is to present several of the best available programs for the analysis of pavement structures in such a way that they can be easily used within the Alaska Department of Transportation and Public Facilities (DOTPF).

The pavement design evaluation methods included in this report are representative of the mechanistic approach. Pavements are analyzed as layered elastic systems in which each material type (layer) is described by its elastic modulus and Poisson's ratio. Stresses and strains are calculated at various locations within the pavement such as might be done in other types of mechanical structures. The engineer can ultimately use these calculated values to estimate roadway performance on the basis of fatigue life and yield strength criteria.

Five programs are fully discussed. Each is unique in some way in terms of input/output complexity and general computational capability. The report suggests uses for each program according to its most practical application. An interesting comparison is made to show variation in output which results when the same set of data is processed through every program.

In order to facilitate the use of computer programs presented in this report, I have written supplemental Appendices B and C. Appendix B contains information concerning the elastic modulus properties of common pavement construction materials. It should provide the reader with some degree of "feeling" for soil and asphalt concrete elastic properties which are necessary as program input variables. Appendix C briefly explains the way in which programs are accessed and run on the Boeing Computer System. Enough information is included so that the reader should be able to utilize any of the five programs discussed in this report. This includes creation, modification, storage and printing of data files and program output files.

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Special recognition is accorded Mr. Alan Braley who made the programs mentioned in this report operational on two different computer systems and provided considerable technical expertise to the project.

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## PREFACE

The present collection of computer programs for the solution of stress and deformation problems in elastic media was assembled by the Department of Civil Engineering, Oregon State University and the U.S. Forest Service, Region 6. The purpose of collecting these programs is to provide pavement designers with a single convenient reference to available, but widely scattered, computer solutions which should be of assistance in the solution of routine and research type problems.

Four of the programs were obtained from the University of California, Berkeley {CHEV5L, CHEV5L w/Iteration (PSAD), PSAD2A and ELSYM5} while the other {SHELL BISAR} was obtained from Shell Oil Company, Houston, Texas. The assistance and cooperation of these agencies is gratefully acknowledged. For any results obtained with the Shell Bisar program, acknowledgment should be made to Koninklijke/Shell-Laboratorium, Amsterdam.

The report would not have been possible without the assistance of U.S. Forest Service, Region 6 and Alaska Department of Transportation. Collection and installation of the programs was initiated while Dr. Hicks was employed by Region 6, U.S. Forest Service. The report was drafted and prepared at Oregon State University. Those who contributed greatly to the completion of the report include Messrs, Chris Schwarzhoff and Ron Williamson, U.S.F.S., Region 6; Robert McHattie, Alaska Department of Transportation; and J. D. Swait, Jr., E. O. Chastain and M. Tobias, students at Oregon State University.

R. G. Hicks

# CHAPTER ONE

# INTRODUCTION

## PURPOSE

The purpose of this report is to provide interested users with a single convenient reference describing computer programs which solve for stresses and deformations in pavement systems. The document provides not only a description of several computer programs, but also includes a user's manual for each.

## SCOPE

The report is divided into three major sections. The first section reviews layered elastic analysis from its inception and attempts to illustrate how it has been used in the design and evaluation of pavement systems. Next, five computer programs are discussed. The final section presents an example problem and its solution with the various programs. The results of each solution are compared and discussed. Potential applications of each program are also discussed. The appendix includes the actual input formats for each program.

# CHAPTER TWO

# LAYERED SYSTEM ANALYSIS

Procedures for prediction of traffic induced deflections, stresses and strains in pavement systems are based on the principle of continuum mechanics. The essential factors that must be considered in predicting the response of layered pavement systems are: (1) the stress-strain behavior of the materials; (2) the initial and boundary conditions of the problem; and (3) the partial differential equations which govern the problem. The highway engineer, however, need only concern himself with the stress-strain behavior of the material, the physical configuration of the problem, and the general assumptions that have been made or implied in developing solutions to the layered system problem.

Reasonably good predictions of pavement response to load can be obtained provided that carefully selected material properties are used with theories employing realistic assumptions. Unfortunately, the solution of the pavement system problem requires the use of a high-speed digital computer. If an engineer selects a formula that is not applicable to his set of conditions, an incorrect answer is obtained; likewise, if a computer program not suited to the particular problem is used, equally poor results are obtained. Therefore, to properly use the theoretical solutions which are now available, an engineer must thoroughly understand the assumptions and limitations associated with the use of these methods.

## ELASTIC LAYERED SYSTEMS

The response of pavement systems to wheel loadings has been of interest since 1926 when Westergaard (1) used elastic layered theory to predict the response of rigid pavements. Later Burmister (2) solved the problem of elastic multilayered pavement structures (Fig. 1) using classical theory of elasticity. The assumptions that Burmister and most others (3,4) have made in developing closed formed solutions are as follows:

1. Each layer acts as a continuous, isotropic, homogeneous, linearly elastic medium infinite in horizontal extent;

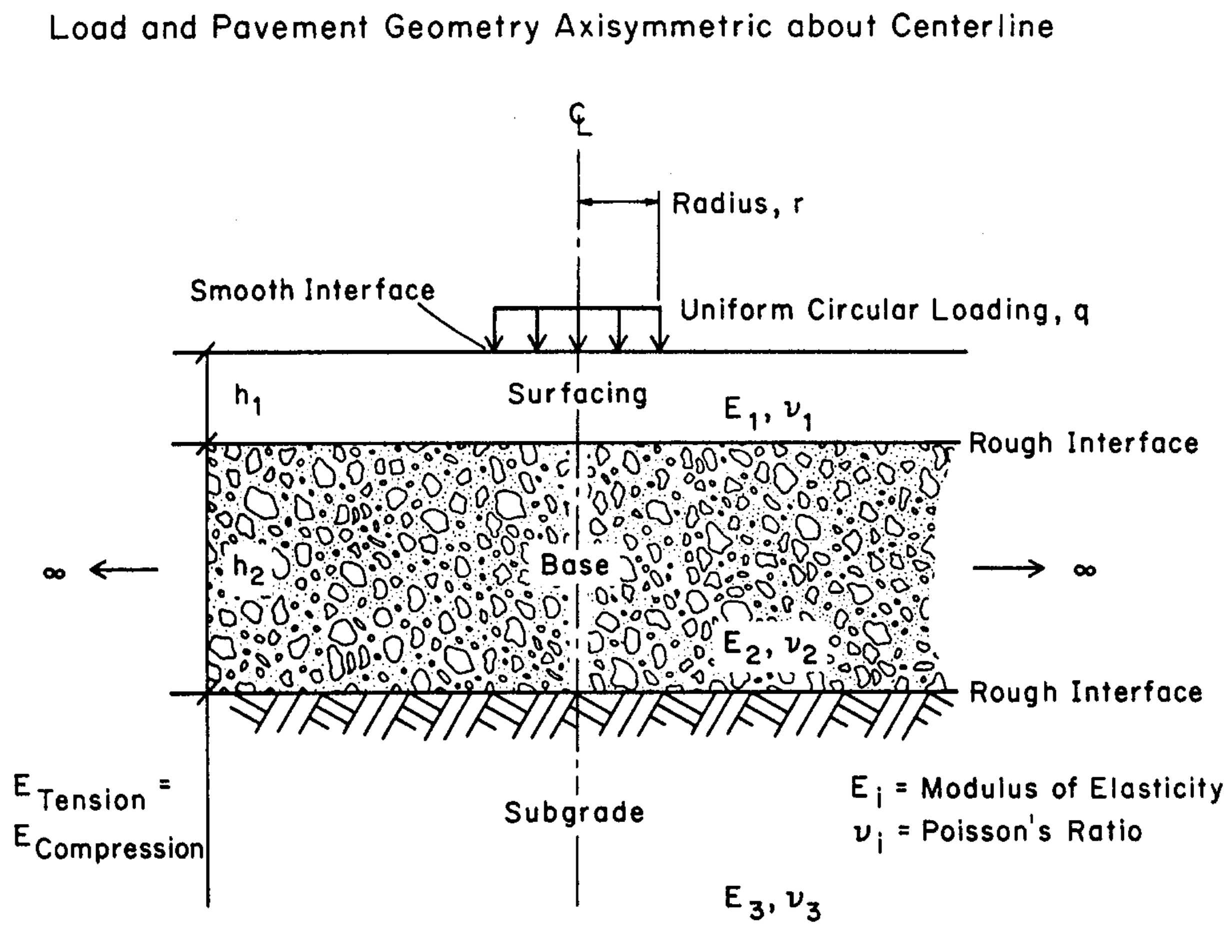



Figure 1. Classical Linear Elastic Layered Pavement Structure Idealization

2. The surface loading can be represented by a uniformly distributed vertical stress over a circular area;
3. The interface conditions between layers can be represented as either perfectly smooth or perfectly rough;
4. Each layer is continuously supported by the layer beneath;
5. Inertial forces are negligible;
6. Deformations throughout the system are small; and
7. Temperature effects are neglected.

The partial differential equations associated with the boundary value problem can be solved by the use of integral transforms (3,4). The response is then obtained in the form of infinite integrals that must be numerically integrated. If a sufficiently close integration interval spacing is not used, or if the integration is not carried out far enough before "chopping" it off, convergence of the integral to the correct value may not occur.

Comprehensive tables and charts of influence values for 2- and 3-layer systems subject to uniform circular loadings are given in the literature (5,6). The use of these tables and charts can be quite tedious and time-consuming for 3-layer pavement systems, and tabulated solutions for 4-layer systems are not practical. Therefore, for general pavement design applications, the use of a computer is a necessity from a practical standpoint.

## LIMITATIONS OF LAYERED THEORY

In classical layered theories, the pavement structure is normally modeled as an axisymmetric solid. Axisymmetry usually means that both load and pavement geometrics are symmetrical about a common centerline. Unfortunately, the effects of wheel loads applied close to a crack or pavement edge cannot be analyzed by the use of methods which require axisymmetry. Although 3-dimensional solid models could be used with finite-element methods, that representation is not practical for general use because of the large amount of computer time required to solve the model. An extended 2-dimensional finite element program that approximates the loading as a Fourier series has been used to study the effects of edge loadings for multiple rectangular wheel loadings (7). Although this approach could lead to a much better understanding of pavement behavior, it also requires too much computer time for general use in a design method.

Information is not available on the conditions of slip which exists at the interface between layers. The assumption of a rough interface condition, which most investigators have used (4,11) appears to be reasonable, although varying degrees of slip can be considered (3).

In all of the theoretical approaches, inertial forces have been neglected. The inertial force is simply the force on a small element caused by a dynamic loading and is equal to the mass of the element times the acceleration. Also, none of the layered system theories consider the effects of vibrations. Neglecting vibrations is probably not a bad assumption for vehicle speeds lower than 96 km/hr (60 mph) on materials that have cohesion. However, for cohesionless materials compacted to lower relative densities, neglecting vibratory effects may lead to densification that would cause rutting and changes in material properties.

Numerous laboratory tests have indicated that the dynamic modulus of paving materials varies with the confining pressure or deviator stress or both (8,9), The modulus is normally given by the following:

$$(M_R) = \frac{\sigma_d}{\varepsilon_r}\text{, psi} \tag{1}$$

where $\sigma_d$ = repeated axial stress, psi
$\varepsilon_r$ = resilient (or elastic) strain

Because of the variation in stress state that exists in each layer of the pavement system, the dynamic modulus actually changes with both depth and lateral position in each layer. Therefore, uncertainties arise in trying to determine what value of dynamic modulus to use in representing each layer in a linear-elastic layered analysis. Furthermore, elastic layered theory cannot consider variations in the modulus with lateral position. Those limitations for the most part can be overcome by the use of nonlinear finite-element theory (8,10). With this technique the pavement response is initially calculated by using assumed moduli for each layer. The calculated stresses are then used to estimate a new stress-dependent modulus from experimentally measured material properties. Additional stress states are then calculated, and the process is repeated by either an iterative or an incremental procedure.

In both cases, the modulus is matched with the stress state in each element. This approach, however, requires considerably more computer time than does a single elastic layered solution.

An excellent alternative approach, which is a practical trade-off, is the use of a nonlinear, iterative elastic layered solution (8,11,12,13). This iterative procedure is analogous to the one used for finite-element theory. In this approach, the base and subgrade can be subdivided into several fictitious layers for better accuracy. The technique uses in each layer a modulus that is dependent on the average stress state which exists in the vicinity beneath the wheel loadings.

## DESIGN IMPLICATIONS

Presently several agencies are adopting the use of elastic layered theory in the design and evaluation of pavement systems (14,15,16,17). Shell (14) has incorporated fatigue in the design of highway pavements since 1963. The criterion developed by Shell has also been used extensively since 1963 in the design and evaluation of pavement systems subjected to unusual wheel loads. The Asphalt Institute followed, using similar, yet more sophisticated, tools to develop a procedure to design and evaluate airfield pavements to account for jumbo jet operations (Manual Series 11) and have just this year (1981) issued a new design manual (Manual Series 1) for use in designing highway pavements (15,16).

The Kentucky Highway Department has also developed a design procedure using layered elastic theory (17). The Chevron program (4) was used in this procedure to calculate stresses and deformations in the pavement systems and design criteria were developed based on observed field performance.

More recently, Chevron Research (18) has developed a "Simplified Thickness Design Procedure for Asphalt and Emulsified Asphalt Pavements." The procedure is based on analysis of layered systems (4) and considers only 2-layered systems (full-depth asphalt pavement design plus subgrade). Critical strains in the pavement system are limited to values depending on expected service life. Thicknesses are then determined to minimize the amount of permanent deformation and/or fatigue cracking.

In all these methods, actual stresses or strains in the pavement layers are used to design flexible pavements against the occurrence of cracking (fatigue) or rutting (permanent deformation) (Figure 2). The tensile strain ($\varepsilon_t$) or stress in the case of cement stabilized layers, is normally limited to preclude fatigue type cracking. The compressive strain ($\varepsilon_c$) on the subgrade is commonly used to preclude rutting. Under a single load, the maximum tensile strain occurs directly beneath the load. In the case of dual or multiple wheels, the maximum strain can occur at other locations. For duals, it could be at points 1, 2 or 3 as shown in Fig. 2.

Once the critical strains or stresses are determined, they are normally compared with limiting values such as given in Fig. 3. Figure 3a shows a typical relationship of tensile strain in the asphalt layer vs. the number of repetitions to failure; for a given value of strain calculated, one can easily estimate the number of repetitions to cause fatigue cracking. Similarly, Fig. 3b shows a relationship used in design to preclude rutting.

Fatigue and/or rutting criteria can be developed either from laboratory or field tests. Most fatigue criteria, such as that shown in Fig. 3a have been developed from laboratory tests, using either laboratory prepared or field samples. To predict pavement life, these laboratory developed criteria are shifted to the right by a factor ranging from as low as 3 to as great as 20, depending on the test (18,23). This is because the fatigue life measured in the field is always greater than that measured in the laboratory. The most important reason for the difference is the effect of rest periods between successive load applications. The curves shown in Fig. 3a have already been shifted to simulate field conditions by a factor of 3 to 5. Most rutting criteria have been developed from field studies. For a given pavement section, the depth of rutting and numbers of repetitions to cause a specific rut depth are recorded. The calculated vertical compressive subgrade strain associated with a given rut depth for the estimated number of load applications can then be established.

In addition to providing users with a capability for better pavement design, layered theory also offers users a method of evaluating pressing problems such as:

1) Impact of increased highway loads; and

2) Effect of using marginal materials on pavement performance.

Many other opportunities may exist for practical use of layered elastic theory. This document should provide engineers with a basic understanding of how to make use of available computer solutions to layered elastic systems.

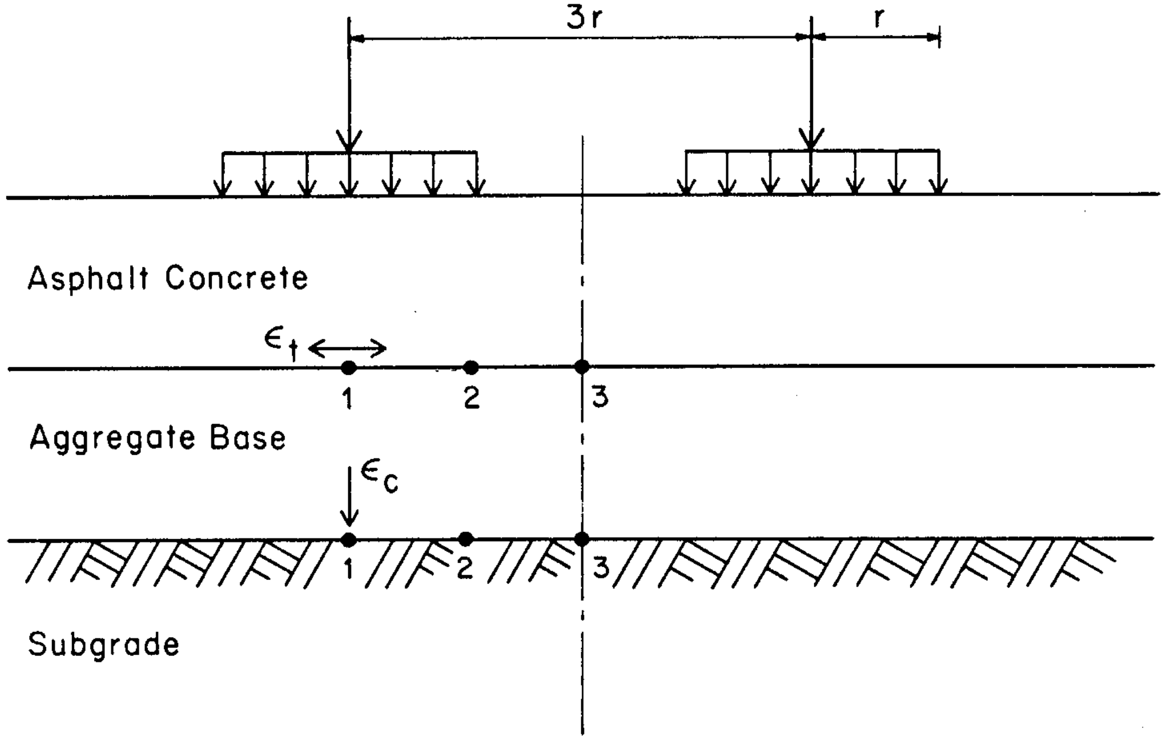



Figure 2. Location of Critical Stresses or Strains in a Layered System

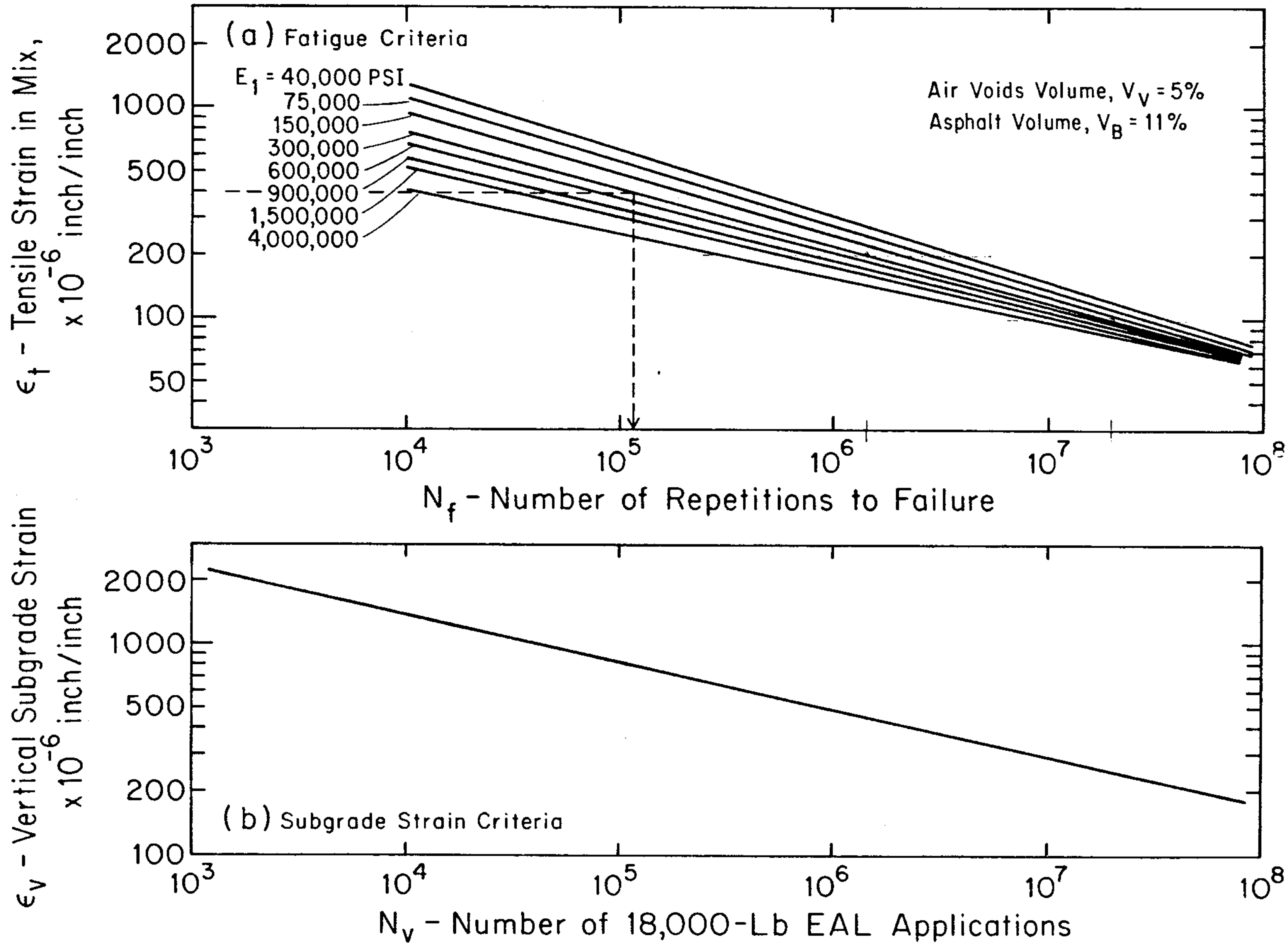



Figure 3 Limiting Strain Criteria to Preclude Fatigue Cracking and Rutting (After reference 18)

## CHAPTER THREE

## COMPUTER PROGRAMS

This chapter presents a detailed discussion of five computer solutions to layered systems. All programs have the capability of solving for stresses, strains and displacements for n-layer systems. The limitations of each program are also included.

### MULTI-LAYERED ELASTIC SYSTEM

#### Description

The Multi-Layered Elastic System computer program (CHEV5L) will determine the various component stresses and strains in a three dimensional ideal elastic layered system with a single vertical uniform circular load at the surface of the system (Fig. 4). The bottom layer of the system is semi-infinite with all other layers of uniform thickness. All layers extend infinitely in the horizontal direction. The top surface of the system is free of shear and all interfaces between layers have full continuity of stresses and displacements.

With a vertical uniform circular load, the system is axisymmetric with the Z axis perpendicular to the layers and extending through the center of the load. Using cylindrical coordinates, any point in the system may be described by R and Z values. R is the horizontal radial distance out from the center of the load and Z is the depth of the point measured vertically from the surface of the system.

The load is described by the total vertical load in pounds and the contact pressure in psi. The load radius is computed by the program. Each layer of the system is described by modulus of elasticity, Poisson's ratio, and thickness in inches. Each layer is numbered, with the top layer as 1 and each layer below numbered consecutively.

#### Program Operating Notes

The program operates with the various given R and Z values as follows: For every R value a complete set of characterizing functions is developed for all layers, then the stresses and strains are computed at those points represented by that R and each of the given Z values. The stresses calculated are shown in Fig. 4. The program then steps to the next R value and

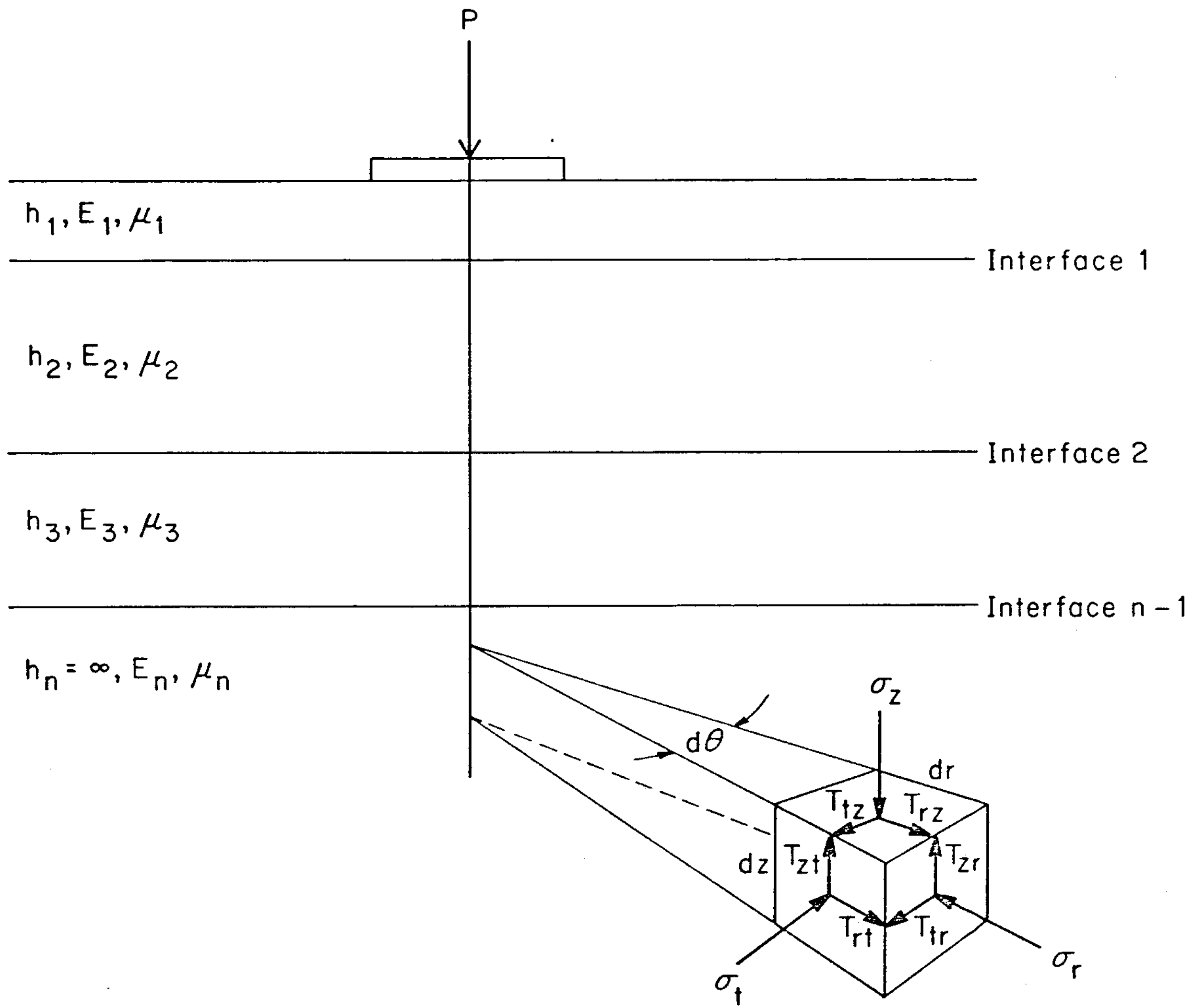



Figure 4. Generalized Multilayered Elastic System (After Reference 22)

computes the stresses and strains at those points represented by each of the given Z values and continues until all combinations of R and Z values are used.

When a given Z value is exactly at an interface between two layers, the program will first compute the stresses and strains at this point using the functions for the upper of the two layers, then will recompute the stresses and strains at this same point using the functions from the lower of the two layers. In the output of the program, a negative Z value indicates that the stresses and strains have been computed at an interface and that the characteristics of the upper layer have been used.

## Limitations

The following are limitations of the program and/or method.

1. Number of layers in the system: minimum of two and a maximum of five.
2. Number of points in the system where stresses and strains are to be determined: minimum of one (one R and one Z) to a maximum of 121 (maximum of eleven R and eleven Z).
3. All data are positive, no negative values.
4. Poisson's ratio must not have a value of one.
5. Nonlinear behavior of granular bases and subgrade soils cannot be taken into account.
6. Multiple gears cannot be handled directly. Calculations of critical stresses and strains under multiple gears must be done using the principle of superposition (by hand).

## MULTI-LAYERED ELASTIC SYSTEM - ITERATIVE METHOD

### Description

The Multi-Layered Elastic System computer program (CHEV5L WITH ITERATION) is also used to determine stresses and strains (Fig. 4) in a three dimensional elastic layered system with a single vertical uniform circular load. The program is an extension of CHEV5L and has the capability of accounting for variations in the modulus of each material with depth.

As with CHEV5L, all layers are assumed to extend indefinitely in the horizontal direction. The top surface is free of shear and all interfaces between layers have full continuity of stresses and displacements. A vertical uniform circular load is applied and stresses, strains and displacements are calculated at any point in the system described by R and Z values. The load is described by the total vertical load in pounds and contact pressure in psi.

Program Operating Notes

The basic difference between CHEV5L and CHEV5L with iteration lies in the method of assigning modulus of elasticity and Poisson's ratio to each layer. Examination of materials characterization studies indicates that the modulus of most materials is dependent on the level of stress (or temperature).

In general, the modulus of cohesive soils decreased with increasing repeated stress level $\sigma_d$ (Fig. 5) and is relatively unaffected by small changes in confining pressure. In this program, the modulus of the subgrade (bottom layer) is interpolated from the input modulus-deviator stress relationship. For materials that are not stress dependent, a horizontal relationship must be input. The variation of Poisson's ratio with stress level is less clear although Hicks and Finn (19) found that it remained constant or increased slightly with increasing deviator stress. Poisson's ratio appears not to be significantly affected by confining pressure.

For unstabilized granular materials, the modulus is most affected by confining pressure and slightly affected by the deviator stress or stress frequency. As shown in Fig. 6, the modulus of granular materials can be approximated by:

$$M_R = k\sigma_3^n$$

or (2)

$$M_R = \bar{k}\theta^{\bar{n}}$$

where k, $\bar{k}$, n, $\bar{n}$ are constants evaluated from repeated load triaxial test results and $\sigma_3$ and $\theta$ are confining pressure and the bulk stress ($\theta=\sigma_1+2\sigma_3$ in a conventional triaxial test), respectively. Poisson's ratio has been found to remain relatively constant over a range of stress conditions (20).

Results of repeated load triaxial tests on emulsion mixes have indicated that, at early stages of cures, confining pressure most affects the modulus.

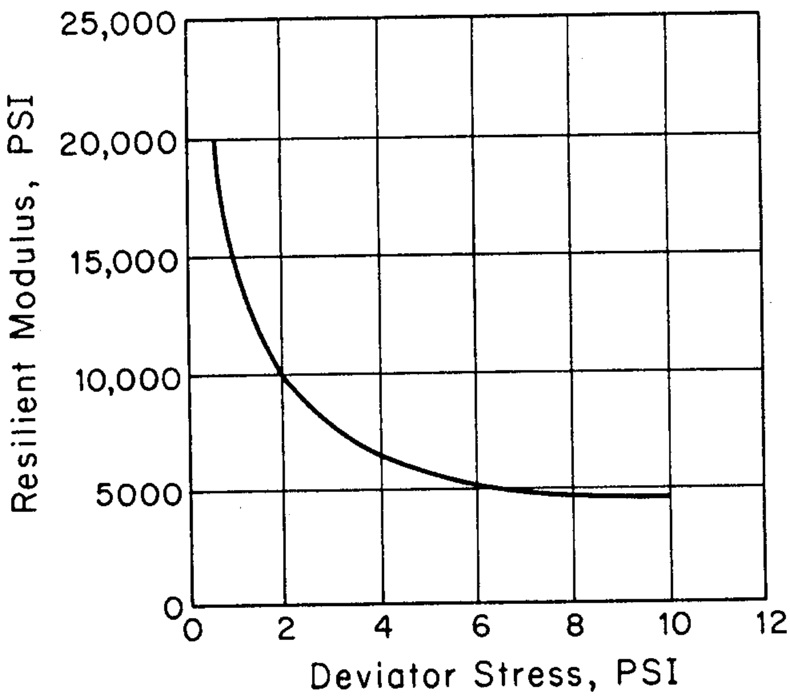



Figure 5. Resilient Modulus vs. Deviator Stress, Subgrade, Morro Bay (After Reference 11)

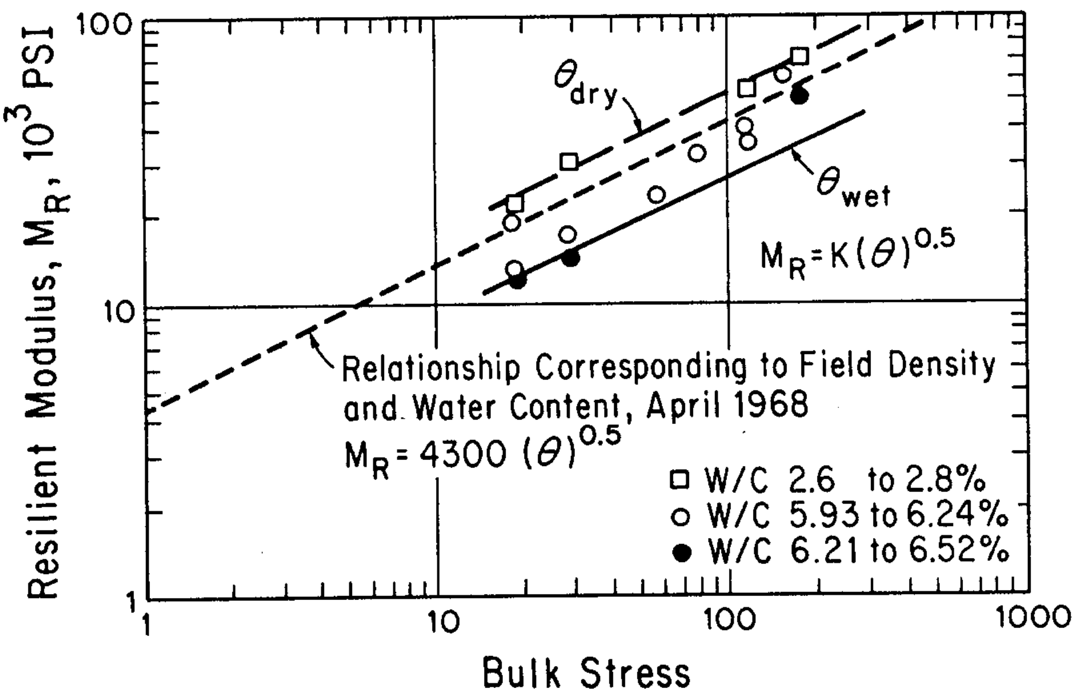



Figure 6. Resilient Modulus as a Function of Bulk Stress ($\theta = \sigma_1 + 2\sigma_3$); Aggregate Base (After Reference 19)

The behavior of these materials is very similar to that of granular bases (Fig. 7). As the curing process progresses, the materials tend to behave more like hot-mix asphalt concrete (Fig. 8). Their properties are most affected by temperature and rate (or frequency) of loading as shown in Fig. 9 (21). Results indicate that Poisson's ratio may increase with increasing temperature and is affected only slightly by stress level.

Because the modulus of most materials are dependent on the level of stress, an iterative approach (in which the modulus and stress level interaction can be allowed to close on a system having compatible values of each) was developed as follows:

1. The pavement to be analyzed can be represented by a number of layers consistent with the dimensions of the structural section.
2. The modulus value and Poisson's ratio for each of these layers can be estimated with some degree of accuracy based on the known variation of these values with the estimated stress and environmental conditions.
3. The stresses which would occur in this system under the application of the surface load can be calculated using available computer solutions.
4. The pre-existing stress state owing to overburden pressures can be calculated from knowledge of the densities and dimensions of the pavement materials.
5. The resulting stress state can be obtained by superposition of the load-induced and overburden stresses.
6. The modulus which is compatible with the resulting stress state in each layer can be determined from the appropriate modulus-stress relationship for the materials.
7. The modulus of each layer required by the stress state can be compared with the initially assumed value and the process repeated, using the resulting values, until the initial and final modulus values coincide within a specified accuracy.

In CHEV5L with iteration, an average modulus under an arbitrary set of dual wheels (center to center spacing of 3R) is calculated using the procedure outlined above. Calculations <u>must</u> be made at the locations indicated in Fig. 10.

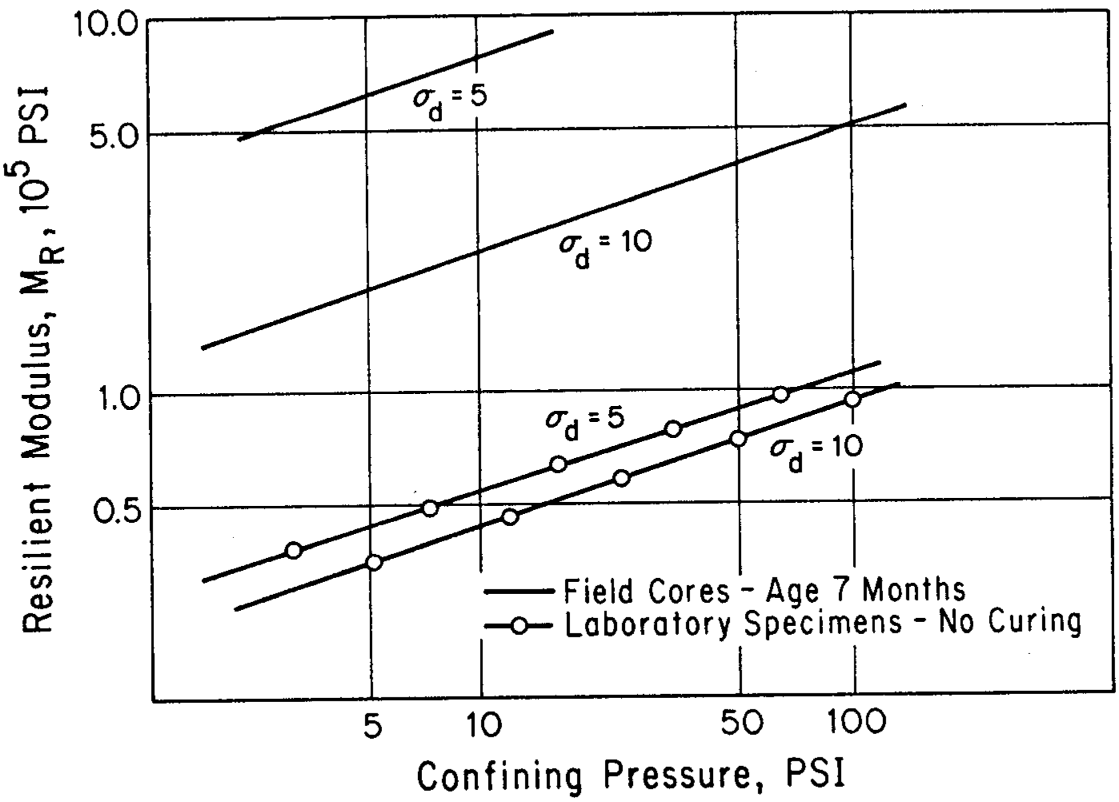



Figure 7. Comparison of Resilient Modulus vs. Confining Pressure for Specimens of Emulsion Treated Special Aggregate at Different Stages of Curing. Note, $\sigma_d$ = repeated stress level (After Reference 19)

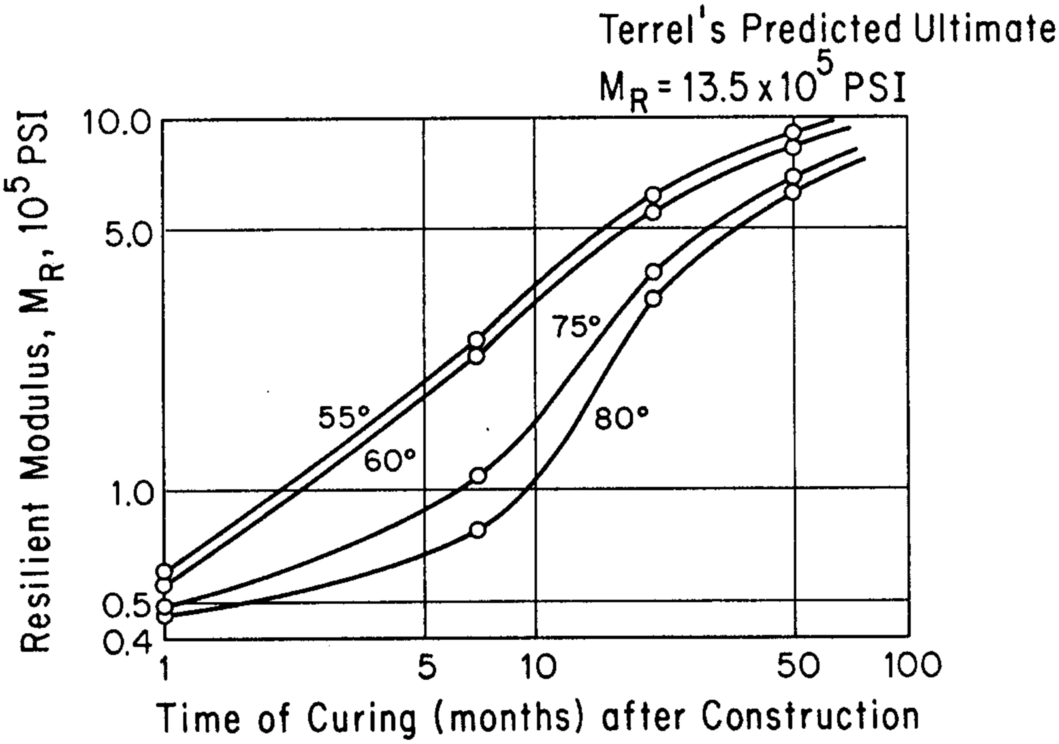



Figure 8. Resilient Modulus vs. Curing Time for Emulsion Treated Aggregates (After Reference 19)

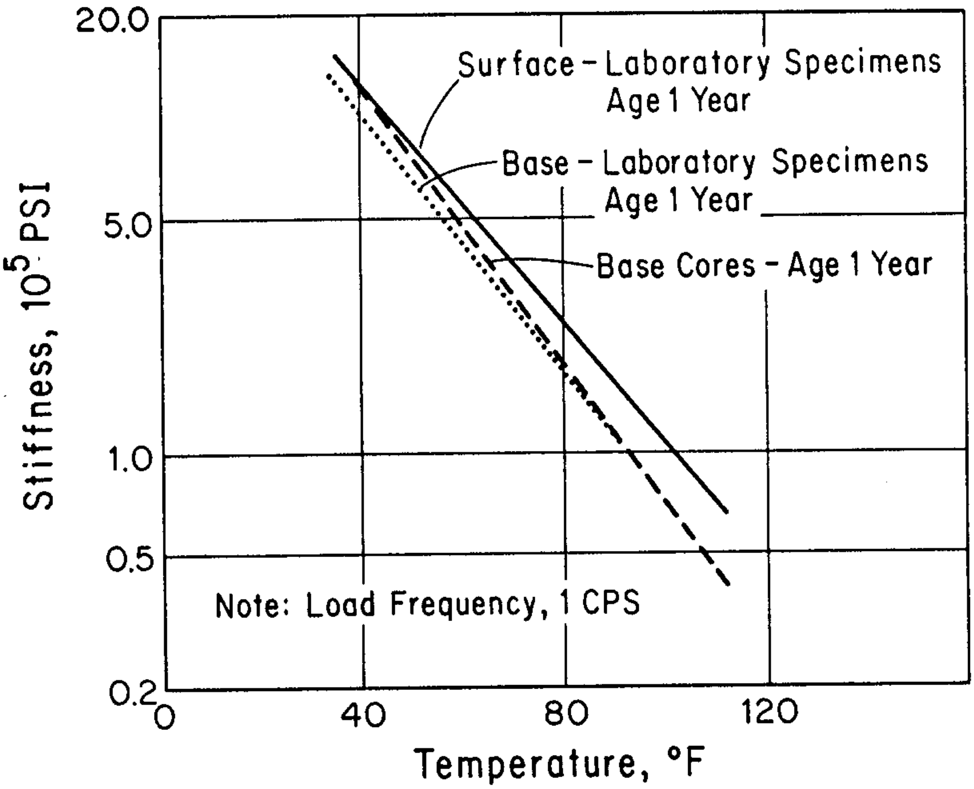



Figure 9. Stiffness Modulus vs. Temperature for Asphalt Concrete Surface and Base (After Reference 19)

Once the iteration process has closed, calculations for stresses, strains and displacements in the system are made (for one wheel loading) as in the case of CHEV5L.

Limitations

The following are limitations of the program and/or method:

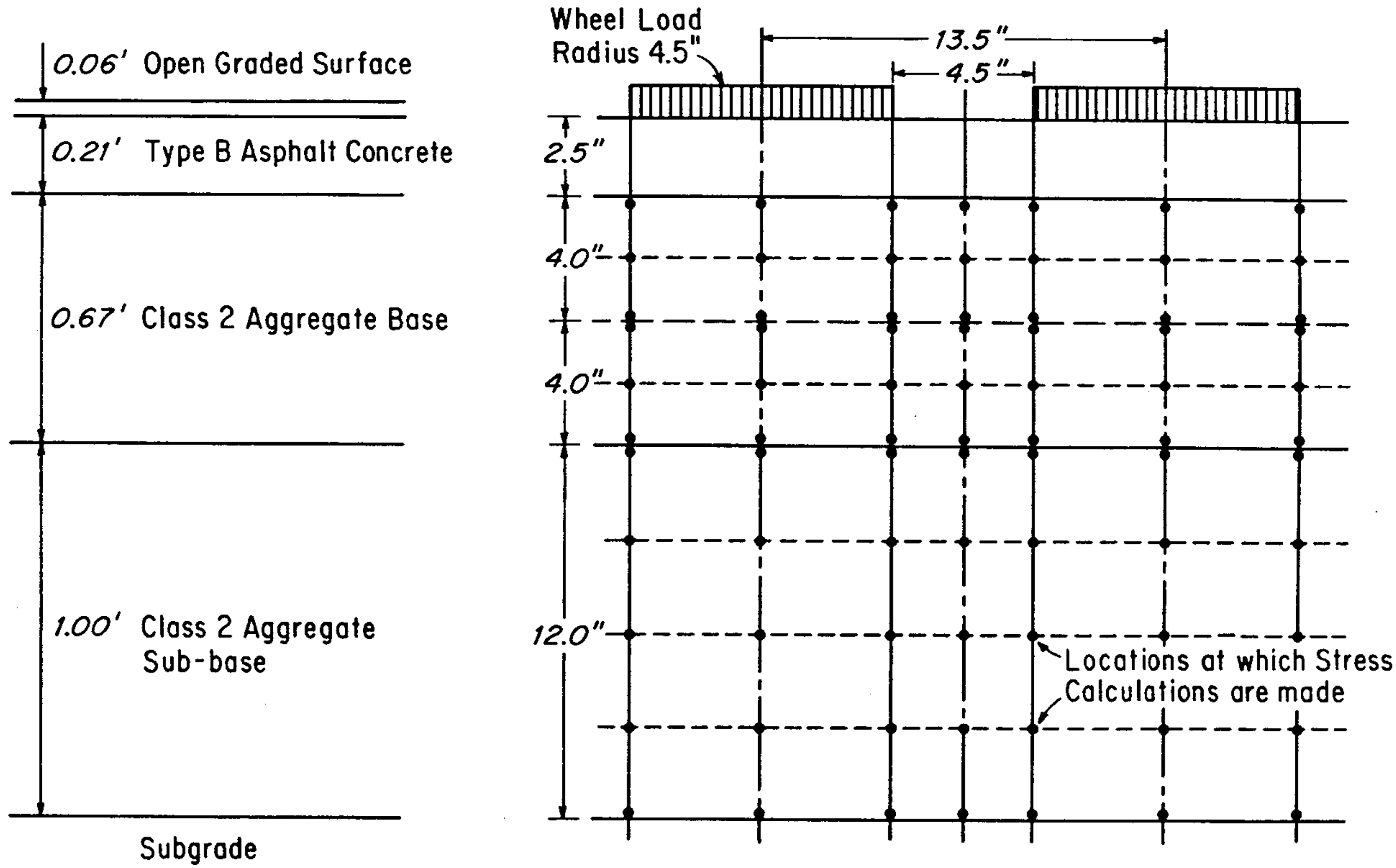
1. Number of layers in system: 5 must be used. (see example problem in Chapter Four).
2. Number of points in system where stresses and strains are to be determined: minimum of 6 (0,1r, 1-1/2r, 2r, 3r, 4r required) to maximum of 11 R values; minimum of 8 (top, middle and of each nonlinear layer) to maximum of 11 Z values; all as shown in Fig. 10.
3. All data are positive, no negative values.
4. Poisson's ratio must not have a value of one.
5. Multiple gears cannot be handled directly. Calculations of critical stresses and strains under multiple gears must be done (by hand) using the principle of superposition.

MULTI-LAYERED ELASTIC SYSTEM - MULTIPLE LOAD OPTION (SHELL BISAR)

Description

The BISAR (Bitumen Structures Analysis in Roads) program is a general purpose program for computing stresses, strains and displacements in elastic layered systems subjected to one or more vertical uniform circular loads applied at the surface of the system. Unlike the CHEV5L programs, the surface loads can be combinations of a vertical normal stress and an unidirectional horizontal stress. All layers extend infinitely in the horizontal direction. The top surface of the system is free of shear. All interfaces between layers have an interface friction factor which can vary between zero (full continuity) and one (frictionless slip) between the layers.

Stresses, strains and displacements are calculated in a cylindrical coordinate system for each vertical load. For more than one load, the cylindrical components are transformed to a Cartesian coordinate system and the effect of the multiple load found by summarizing the stresses, strains and displacements of each wheel. Further, the program calculates only those




(a) Structural Section (b) Computer Representation

Figure 10 Morro Bay Pavement, (V-SLO-56-C,0) (After Reference 11) components which are requested (Table 1)*. If all stresses and strains are calculated, the program calculates the principal stresses and strains and their accompanying directions. The principal directions denote the normals of the planes through the point considered, which are free of shear stress (strain). The highest and lowest of the three principal values give the maximum and minimum normal stresses (strains), and the difference between the principal values divided by two, gives the maximum shear stresses (strains).

For a given problem to be solved using the BISAR program, one needs information regarding:

1. The number of layers;
2. Young's modulus and Poisson's ratio of each layer;
3. The thickness of each layer, except for the bottom one;
4. The interface friction at each interface;
5. The number of loads, the vertical and tangential component of each load, and the position of the loads;
6. The stress, strain and displacement components to be calculated;
7. The number of places where calculations are required along with their position (Cartesian coordinates).

Program Operating Notes:

BISAR consists of a main program and 24 subprograms. The main program reads all the input data defining the numerical problem and controls the subsequent steps in the calculation of the requested stresses, strains and displacements. The output is partly controlled by the main program and by subprograms SYSTEM, CALC, and OUTPUT. Subprograms MACON1, CONPNT, INGRAL and MATRIX give output only when error messages are generated.

The main program can consider several multilayered systems in one run (to a maximum of 99). For each multilayer system, the stresses, strains and displacements can be calculated in an arbitrary number of different positions (to a maximum of 99). Computation proceeds by calculating at each point the stresses, strains and displacements due to each load separately and by transforming these to the Cartesian coordinate system. The Cartesian components are added to those of the preceding loads and by the time the last load has been considered, the total stresses, strains and displacements have been calculated. The computed results are printed (separately) for each position requested.

* Any or all of the types of computations may be requested.

TABLE 1. STRESSES, STRAINS AND DISPLACEMENTS CALCULATED BY BISAR*

| | | | |
|---|---|---|---|
| Displacements | UR | - | Radial Displacement |
| | UT | - | Tangential Displacement |
| | UZ | - | Vertical Displacement |
| Stresses | SRR | - | Radial Stress |
| | STT | - | Tangential Stress |
| | SZZ | - | Vertical Stress |
| | SRT | - | Radial/Tangential |
| | SRZ | - | Radial/Vertical |
| | STZ | - | Tangential/Vertical |
| Strains | ERR | - | Radial Strain |
| | ETT | - | Tangential Strain |
| | EZZ | - | Vertical Strain |
| | ERT | - | Radial/Tangential |
| | ERZ | - | Radial/Vertical |
| | ETZ | - | Tangential/Vertical |
| Total Displacements | UX | - | x-displacement |
| | UY | - | y-displacement |
| Total Stresses | SXX | - | xx component of Total Stress |
| | SXY | - | xy component of Total Stress |
| | SXZ | - | xz component of Total Stress |
| | SYY | - | yy component of Total Stress |
| | SYZ | - | yz component of Total Stress |
| Total Strains | EXX | - | xx component of Total Strain |
| | EXY | - | xy component of Total Strain |
| | EXZ | - | xz component of Total Strain |
| | EYY | - | yy component of Total Strain |
| | EYZ | - | yz component of Total Strain |

* For additional details, see reference 24.

Limitations

The following are limitations of the program and/or method:

1. Number of layers in the system: maximum of ten, although this can be changed with modifications to the program.
2. Number of systems in one run: maximum of 99.
3. Number of points in the system where stresses and strains can be calculated: maximum of 99.
4. Nonlinear behavior of granular bases and subgrade soils cannot be accounted for.

## MULTI-LAYERED SYSTEM-MULTIPLE LOAD OPTION (ELSYM5)*

### Description

The Elastic Layered System computer program (ELSYM5) will determine the various component stresses, strains and displacements along with principal values in a three-dimensional ideal elastic layered system, the layered system being loaded with one or more identical uniform circular loads normal to the surface of the system.

The top surface of the system is free of shear. Each layer is of uniform thickness and extends infinitely in the horizontal direction. All elastic layer interfaces are continuous. The bottom elastic layer may be semi-infinite in thickness or may be given a finite thickness, in which case the program assumes the bottom elastic layer is supported by a rigid base. With a rigid base, the interface between the bottom elastic layer and the base has to be made either fully continuous or slippery.

All locations within the system are described by using the rectangular coordinate system (X,Y,Z) with the XY plane at Z - 0 being the top surface of the elastic system where the loads are applied. The positive Z axis extends vertically down from the surface into the system.

The applied loads are described by any two of the three following items: load in pounds, stress in pounds per square inch, radius of loaded area in inches. The program determines the missing value. Each layer of the system is described by modulus of elasticity, Poisson's ratio and thickness. Each layer is numbered with the top layer as one and numbering each layer consecutively downward.

### Program Operating Notes

The program tests all input data. If any input data is out of range as specified under "Limitations," the problem is terminated for that system with an error message and the program goes on to the next system for operation.

The program uses the convention that compressive stresses are negative and tensile stresses are positive.

The output of the program gives for each depth (Z) all the results for all the XY points. The results for each point are the total results for

---

* This write-up is from text written by Gale Ahlborn, ITTE, University of California at Berkeley, 1972.

that point obtained by summing the contribution by each load. When a Z value is determined to be on an interface, the results are determined using the characteristics of the upper of the two layers.

## Limitations

Following are the limitations of the program and/or method.

1. Number of different systems for solution: minimum of one, maximum of five.
2. Number of elastic layers in the system: Minimum of one, maximum of five.
3. Number of identical uniform circular loads: minimum of one, maximum of ten.
4. Nonlinear behavior of granular bases and subgrade soils cannot be accounted for.
5. Number of points in the system where results are desired: minimum of one (one XY and one Z), maximum of 100 (ten XY and ten Z).
6. Where there is a rigid base specified, the maximum Z value cannot exceed the depth to the rigid base.
7. All input values except XY positions must be positive.
8. Poisson's ratio must not have a value of one. Poisson's ratio for a bottom elastic layer on a rigid base must not be within the range of 0.748 to 0.752.
9. The program uses a truncated series for the integration process that leads to some approximation for the results at and near the surface and at points out at some distance from the load.

## MULTI-LAYER ELASTIC THEORY ITERATIVE METHOD-DUAL WHEEL OPTION (PSAD2A)*

## Description

PSAD2A is essentially the same as CHEV5L w/iteration except that the former has the added capability of printing stresses, strains, and displacements due to dual wheel configurations. This feature of PSAD2A is not an option; it is performed automatically.

* Write-up is based on an excerpt from Report TE 70-5, ITTE, University of California at Berkeley, 1973 (12).

## Program Operating Notes

In the case of dual wheels, PSAD2A allows the distance between loads (from edge to edge) to vary between zero and two load radii for the calculation of an average modulus when iterating, whereas CHEV5L w/iteration fixes this distance at one load radii. This can be inferred from the operating notes on CHEV5L w/iteration, where it is stated that an average modulus is calculated under an arbitrary set of dual wheels spaced three radii center to center.

Other than this one difference, the solution method used in PSAD2A is the same as that used by CHEV5L w/iteration.

## Limitations

1. The number of data sets for the relationship between resilient modulus and deviator stress for the subgrade must be at a minimum two and at a maximum twenty. A number outside this range will result in an error message and termination of the run.
2. The relationship between resilient modulus and deviator stress for the subgrade may be constant or have negative slope, but the first point must have an abscissa (i.e. stress value) of zero. This may require backward extrapolation of experimental data.
3. Five layers must be used.
4. Consult appropriate limitations for CHEV5L w/iteration.

# CHAPTER FOUR

# DISCUSSION

## EXAMPLE PROBLEM

To check the operational characteristics of the various programs, an example problem (Fig. 11) was solved, and the output of the various programs compared. The problem (a 3-layered elastic system) represents essentially a full depth asphalt layer over a weak subgrade. Each layer is characterized by a modulus ($E_i$) and Poisson's ratio ($\nu_i$). The load is a 9000 lb wheel load uniformly distributed with a contact pressure of 80 psi. It should be noted that the contact pressure does not necessarily equal the tire pressure.*

Input formats for each of the programs are discussed in detail in Appendix A. However, Fig. 12 illustrates the data input for the example problem for each of the five programs.

Note, the basic input consists of:

1) wheel load data;
2) material properties of each layer; and
3) thickness of each layer.

Also input are the locations at which calculations are requested. In this particular problem, solutions for stresses and deformations are requested at the surface and at the interfaces of each layer. Calculations are called for at the center (0) and the edge of the loaded area (5.98 inch).

## COMPARISON OF RESULTS

For the example problem presented in Fig. 11, the calculated stresses, strains, and deformations are nearly identical. Figure 13 is a sample of the output of each program. Items which should be noted are as follows:

1. Stresses. CHEV5L, CHEV5L w/iteration, and PSAD2A output vertical, tangential, radial, shear, and bulk stresses for each position expressed in terms of cylindrical coordinates. Each of these stresses is identified in Fig. 3. ELSYM5 calculates normal, shear, and principal stresses, presenting them for each position expressed

* If the effect of tire wall is ignored, the contact pressure between the tire and pavement must be equal to the tire pressure. For high pressure tires, contact pressures under the tire are greater near the center. For low pressure tires the reverse is true (21).

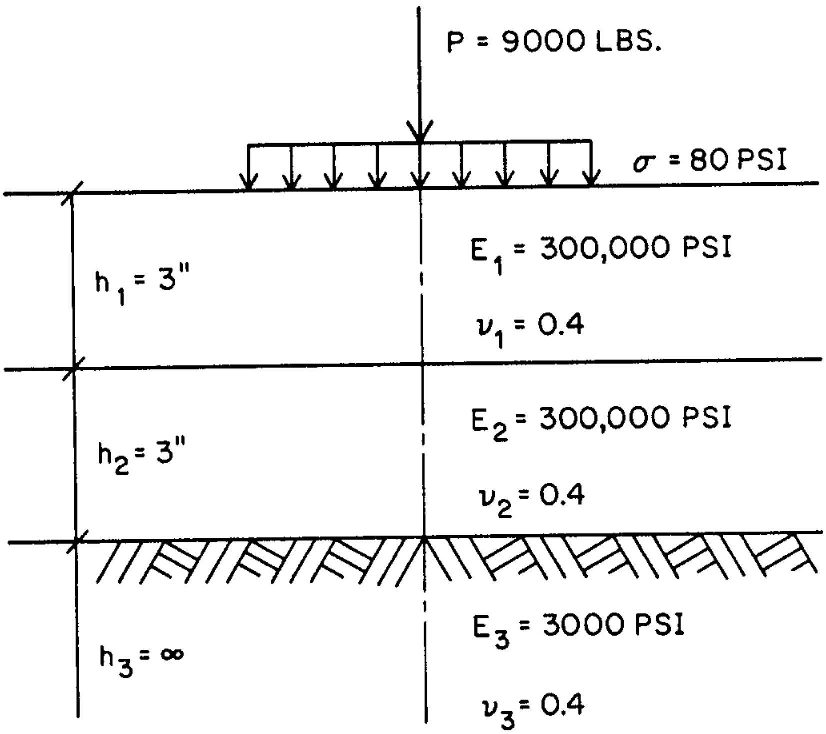



Figure 11. Example Problem - Layered Analysis

```
FORTRAN STATEMENT

    1
TRIAL RUN PSAD2A  R.G. HICKS  7-13-81
     9ØØØ.       8Ø.                      1.    3
   3ØØØØØ.        .4  3ØØØØØ.             Ø.        15Ø.          1.5
   3ØØØØØ.        .4  3ØØØØØ.             Ø.        15Ø.          1.5
   3ØØØØØ.        .4  3ØØØØØ.             Ø.        15Ø.          1.5
   3ØØØØØ.        .4  3ØØØØØ.             Ø.        15Ø.          1.5
      3ØØØ.       .4
         Ø.    3ØØØ.       1Ø.      3ØØØ.            2Ø.       3ØØØ.
```

a) PSAD2A

```
FORTRAN STATEMENT

    1
999 TRIAL RUN ELSYM5   R.G. HICKS  7-13-81
    3    1    2    3
    1   3.   .4   3ØØØØØØ.
    2   3.   .4   3ØØØØØ.
    3        .4   3ØØØ.
     9ØØØ.        8Ø.
        Ø.        Ø.
        Ø.        Ø.
        Ø.        5.98
   Ø.   3.   6.
```

b) ELSYM5

```
FORTRAN STATEMENT

TRIAL RUN CHEV5L  R.G. HICKS  7-13-81
      9ØØØ.          8Ø.
 3 3ØØØØØ.   .4 3ØØØØØ.     .4   3ØØØ.     .4
    3.       3.
     2       Ø.  5.98
     3       Ø.   3.     6.
```

c) CHEV5L

```
EXAMPLE USING CHEV5L W/ ITERATION (OPTION 1)

FORTRAN STATEMENT

    1
CHEV5L WITH ITERATION  R.G. HICKS  7-13-81
     9ØØØ.          8Ø.                       1
 3 3ØØØØØ.    .4 3ØØØØØ.     .4    3ØØØ.     .4
   3ØØØØØ.         Ø.     3ØØØØØ.        Ø.
      15Ø.       15Ø.
3      Ø.   3ØØØ.    1Ø.    3ØØØ.    2Ø.   3ØØØ.
    3.      3.
     2      Ø.  5.98
     3      Ø.   3.     6.
```

d) CHEV5L w/Iteration (Option 1)

Figure 12 Input for Example Problem

EXAMPLE USING CHEV5L W/ ITERATION (OPTION 2)

```
    1
CHEV5L WITH ITERATION   R.G. HICKS   7-13-81
       9ØØØ.            8Ø.               2     2
 5 3ØØØØØ.      .4 3ØØØØØ.     .9 3ØØØØØ.     .4 3ØØØØØ.     .4   3ØØØ.    .4
   3ØØØØØ.           Ø.    3ØØØØØ.         Ø.   3ØØØØØ.        Ø.   3ØØØØØ.      Ø.
      15Ø.          15Ø.        15Ø.        15Ø.
 3    Ø.     3ØØØ.        1Ø.    3ØØØ.       2Ø.   3ØØØ.
   1.5    1.5   1.5   1.5
     6     Ø.  5.98  8.98  11.97  17.95  23.94
     8     Ø.  1.5   2.25     3.   3.75    4.5   5.25    6.
```

e) CHEV5L w/Iteration (Option 2)

```
SHELL BISAR TRIAL RUN   R.G. HICKS                              8  4  1981
 1
 3
      3.ØEØ5       4.ØE-Ø1          3.ØEØØ
      3.ØEØ5       4.ØE-Ø1          3.ØEØØ
      3.ØEØ3       4.ØE-Ø1
 1
STRS          8.ØEØ1      5.984EØØ
UR UT U2 SRRSTTTS22             ERRETTE22
 8
 1
 1                  5.98EØØ
 1                                  3.ØØEØØ
 2                  5.98EØØ         3.ØØEØØ
 2                                  6.ØØEØØ
 2                  5.98EØØ         6.ØØEØØ
 3                                  6.ØØEØØ
 3                  5.98EØØ         6.ØØEØØ
```

f) Shell BISAR

Figure 12. Input for Example Problem (Continued)

******************* TRIAL RUN CHEV5L WITH ITERATION (2) R.G. HICKS 10-14-81 ******************* PAGE 1

THE PROBLEM PARAMETERS ARE

TOTAL LOAD.. 9000.00 LBS

TIRE PRESSURE.. 80.00 PSI

LOAD RADIUS.. 5.98 IN.

LAYER 1 HAS MODULUS 300000. POISSONS RATIO .400 AND THICKNESS 1.5 IN.
LAYER 2 HAS MODULUS 300000. POISSONS RATIO .400 AND THICKNESS 1.5 IN.
LAYER 3 HAS MODULUS 300000. POISSONS RATIO .400 AND THICKNESS 1.5 IN.
LAYER 4 HAS MODULUS 300000. POISSONS RATIO .400 AND THICKNESS 1.5 IN.
LAYER 5 HAS MODULUS 3000. POISSONS RATIO .400 AND IS SEMI-INFINITE.

| | | STRESSES | | | | | DISPLACEMENT | STRAINS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R | Z | VERTICAL | TANGENTIAL | RADIAL | SHEAR | BULK | VERTICAL | RADIAL | TANGENTIAL | SHEAR | |
| 0.0 | 0.0 | -8.C00E+01 | -2.847E+02 | -2.847E+02 | C. | -6.495E+02 | 6.032E-02 | -4.628E-04 | -4.628E-04 | 0. | SLOW |
| 0.0 | -1.5 | -7.614E+01 | -1.398E+02 | -1.398E+02 | 0. | -3.498E+02 | 6.078E-02 | -1.861E-04 | -1.861E-04 | 0. | |
| 0.0 | 1.5 | -7.614E+01 | -1.398E+02 | -1.398E+02 | 0. | -3.498E+02 | 6.078E-02 | -1.861E-04 | -1.861E-04 | 0. | |
| 0.0 | 2.3 | -5.930E+01 | -7.436E+01 | -7.436E+01 | 0. | -2.080E+02 | 6.083E-02 | -6.966E-05 | -6.966E-05 | 0. | |
| 0.0 | -3.0 | -4.617E+01 | -1.158E+01 | -1.158E+01 | 0. | -6.934E+01 | 6.078E-02 | 3.840E-05 | 3.840E-05 | 0. | |
| 0.0 | 3.0 | -4.617E+01 | -1.158E+01 | -1.158E+01 | 0. | -6.934E+01 | 6.078E-02 | 3.840E-05 | 3.840E-05 | 0. | |
| 0.0 | 3.8 | -3.240E+01 | 5.042E+01 | 5.042E+01 | 0. | 6.843E+01 | 6.064E-02 | 1.440E-04 | 1.440E-04 | 0. | |
| 0.0 | -4.5 | -1.986E+01 | 1.138E+02 | 1.138E+02 | 0. | 2.078E+02 | 6.042E-02 | 2.542E-04 | 2.542E-04 | 0. | |
| 0.0 | 4.5 | -1.986E+01 | 1.138E+02 | 1.138E+02 | 0. | 2.078E+02 | 6.042E-02 | 2.542E-04 | 2.542E-04 | 0. | |
| 0.0 | 5.3 | -1.059E+01 | 1.811E+02 | 1.811E+02 | 0. | 3.517E+02 | 6.008E-02 | 3.764E-04 | 3.764E-04 | 0. | |
| 0.0 | -6.0 | -6.766E+00 | 2.549E+02 | 2.549E+02 | C. | 5.031E+02 | 5.963E-02 | 5.189E-04 | 5.189E-04 | 0. | |
| 0.0 | 6.0 | -6.766E+00 | -1.917E+00 | -1.917E+00 | 0. | -1.060E+01 | 5.963E-02 | 5.189E-04 | 5.189E-04 | 0. | |
| 6.0 | 0.0 | -4.126E+01 | -2.121E+02 | -1.835E+02 | 4.880E-13 | -4.369E+02 | 5.653E-02 | -2.740E-04 | -4.073E-04 | -2.435E-03 | SLOW |
| 6.0 | -1.5 | -3.308E+01 | -9.738E+01 | -9.527E+01 | -4.517E+01 | -2.257E+02 | 5.692E-02 | -1.436E-04 | -1.535E-04 | -9.177E-04 | |
| 6.0 | 1.5 | -3.308E+01 | -9.738E+01 | -9.527E+01 | -4.517E+01 | -2.257E+02 | 5.692E-02 | -1.436E-04 | -1.535E-04 | -9.177E-04 | |
| 6.0 | 2.3 | -2.758E+01 | -4.932E+01 | -5.292E+01 | -4.833E+01 | -1.298E+02 | 5.699E-02 | -7.387E-05 | -5.708E-05 | -3.413E-04 | |
| 6.0 | -3.0 | -2.162E+01 | -3.224E+00 | -1.110E+01 | -4.770E+01 | -3.594E+01 | 5.699E-02 | -3.870E-06 | 3.288E-05 | 1.966E-04 | |
| 6.0 | 3.0 | -2.162E+01 | -3.224E+00 | -1.110E+01 | -4.770E+01 | -3.594E+01 | 5.699E-02 | -3.870E-06 | 3.288E-05 | 1.966E-04 | |
| 6.0 | 3.8 | -1.580E+01 | 4.247E+01 | 3.057E+01 | -4.329E+01 | 5.724E+01 | 5.691E-02 | 6.633E-05 | 1.219E-04 | 7.289E-04 | |
| 6.0 | -4.5 | -1.073E+01 | 8.919E+01 | 7.248E+01 | -3.472E+01 | 1.509E+02 | 5.676E-02 | 1.370E-04 | 2.150E-04 | 1.286E-03 | |
| 6.0 | 4.5 | -1.073E+01 | 8.919E+01 | 7.248E+01 | -3.472E+01 | 1.509E+02 | 5.676E-02 | 1.370E-04 | 2.150E-04 | 1.286E-03 | |
| 6.0 | 5.3 | -7.056E+00 | 1.394E+02 | 1.150E+02 | -2.115E+01 | 2.463E+02 | 5.653E-02 | 2.083E-04 | 3.173E-04 | 1.897E-03 | |
| 6.0 | -6.0 | -5.526E+00 | 1.916E+02 | 1.585E+02 | -1.062E+00 | 3.446E+02 | 5.622E-02 | 2.800E-04 | 4.349E-04 | 2.601E-03 | |
| 6.0 | 6.0 | -5.526E+00 | -1.731E+00 | -2.063E+00 | -1.062E+00 | -9.319E+00 | 5.622E-02 | 2.800E-04 | 4.349E-04 | 2.601E-03 | |
| 9.0 | 0.0 | -2.478E-01 | -1.381E+02 | -9.609E+01 | 2.650E-13 | -2.345E+02 | 5.302E-02 | -1.358E-04 | -3.320E-04 | -2.981E-03 | SLOW |
| 9.0 | -1.5 | -3.137E-01 | -6.758E+01 | -5.752E+01 | -2.385E+01 | -1.254E+02 | 5.338E-02 | -1.012E-04 | -1.482E-04 | -1.331E-03 | |
| 9.0 | 1.5 | -3.137E-01 | -6.758E+01 | -5.752E+01 | -2.385E+01 | -1.254E+02 | 5.338E-02 | -1.012E-04 | -1.482E-04 | -1.331E-03 | |
| 9.0 | 2.3 | -1.167E+00 | -3.391E+01 | -3.438E+01 | -3.087E+01 | -6.946E+01 | 5.347E-02 | -6.783E-05 | -6.563E-05 | -5.894E-04 | |
| 9.0 | -3.0 | -2.165E+00 | -5.362E-01 | -9.412E+00 | -3.374E+01 | -1.211E+01 | 5.351E-02 | -2.777E-05 | 1.365E-05 | 1.226E-04 | |

******************* TRIAL RUN CHEV5L WITH ITERATION (2) R.G. HICKS 10-14-81 ******************* PAGE 2

| | | STRESSES | | | | | DISPLACEMENT | STRAINS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R | Z | VERTICAL | TANGENTIAL | RADIAL | SHEAR | BULK | VERTICAL | RADIAL | TANGENTIAL | SHEAR | |
| 9.0 | 3.0 | -2.165E+00 | -5.362E-01 | -9.412E+00 | -3.374E+01 | -1.211E+01 | 5.351E-02 | -2.777E-05 | 1.365E-05 | 1.226E-04 | |
| 9.0 | 3.8 | -3.062E+00 | 3.299E+01 | 1.634E+01 | -3.231E+01 | 4.627E+01 | 5.348E-02 | 1.454E-05 | 9.227E-05 | 8.286E-04 | |
| 9.0 | -4.5 | -3.778E+00 | 6.714E+01 | 4.191E+01 | -2.652E+01 | 1.053E+02 | 5.339E-02 | 5.522E-05 | 1.730E-04 | 1.553E-03 | |
| 9.0 | 4.5 | -3.778E+00 | 6.714E+01 | 4.191E+01 | -2.652E+01 | 1.053E+02 | 5.339E-02 | 5.522E-05 | 1.730E-04 | 1.553E-03 | |
| 9.0 | 5.3 | -4.294E+00 | 1.024E+02 | 6.638E+01 | -1.621E+01 | 1.645E+02 | 5.324E-02 | 9.048E-05 | 2.585E-04 | 2.322E-03 | |
| 9.0 | -6.0 | -4.482E+00 | 1.392E+02 | 8.862E+01 | -1.112E+00 | 2.234E+02 | 5.304E-02 | 1.157E-04 | 3.519E-04 | 3.160E-03 | |
| 9.0 | 6.0 | -4.482E+00 | -1.566E+00 | -2.072E+00 | -1.112E+00 | -8.120E+00 | 5.304E-02 | 1.157E-04 | 3.519E-04 | 3.160E-03 | |
| 12.0 | 0.0 | 2.720E-01 | -1.047E+02 | -5.791E+01 | 9.547E-13 | -1.623E+02 | 4.937E-02 | -5.381E-05 | -2.721E-04 | -3.258E-03 | SLOW |
| 12.0 | -1.5 | -4.178E-01 | -5.210E+01 | -3.364E+01 | -1.648E+01 | -8.616E+01 | 4.962E-02 | -4.213E-05 | -1.282E-04 | -1.535E-03 | |
| 12.0 | 1.5 | -4.178E-01 | -5.210E+01 | -3.364E+01 | -1.648E+01 | -8.616E+01 | 4.962E-02 | -4.213E-05 | -1.282E-04 | -1.535E-03 | |
| 12.0 | 2.3 | -9.143E-01 | -2.656E+01 | -1.984E+01 | -2.081E+01 | -4.732E+01 | 4.968E-02 | -2.952E-05 | -6.084E-05 | -7.283E-04 | |
| 12.0 | -3.0 | -1.568E+00 | -1.266E+00 | -5.469E+00 | -2.246E+01 | -8.304E+00 | 4.971E-02 | -1.445E-05 | 5.162E-06 | 6.178E-05 | |
| 12.0 | 3.0 | -1.568E+00 | -1.266E+00 | -5.469E+00 | -2.246E+01 | -8.304E+00 | 4.971E-02 | -1.445E-05 | 5.162E-06 | 6.178E-05 | |
| 12.0 | 3.8 | -2.287E+00 | 2.402E+01 | 9.046E+00 | -2.135E+01 | 3.078E+01 | 4.969E-02 | 1.180E-06 | 7.104E-05 | 8.504E-04 | |
| 12.0 | -4.5 | -2.968E+00 | 4.953E+01 | 2.321E+01 | -1.741E+01 | 6.977E+01 | 4.963E-02 | 1.530E-05 | 1.381E-04 | 1.653E-03 | |
| 12.0 | 4.5 | -2.968E+00 | 4.953E+01 | 2.321E+01 | -1.741E+01 | 6.977E+01 | 4.963E-02 | 1.530E-05 | 1.381E-04 | 1.653E-03 | |
| 12.0 | 5.3 | -3.472E+00 | 7.550E+01 | 3.648E+01 | -1.062E+01 | 1.085E+02 | 4.953E-02 | 2.557E-05 | 2.076E-04 | 2.486E-03 | |
| 12.0 | -6.0 | -3.648E+00 | 1.022E+02 | 4.831E+01 | -1.024E+00 | 1.468E+02 | 4.939E-02 | 2.968E-05 | 2.810E-04 | 3.364E-03 | |
| 12.0 | 6.0 | -3.648E+00 | -1.386E+00 | -1.925E+00 | -1.024E+00 | -6.959E+00 | 4.939E-02 | 2.968E-05 | 2.810E-04 | 3.364E-03 | |

Figure 13a Output for Example Problem (CHEV5L and CHEV5L with iteration)

```
ELSYM5  3/72 - 3.  ELASTIC LAYERED SYSTEM WITH ONE TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 - TRIAL RUN ELSYM5  R.G. HICKS  10-14-81

  Z=    0.00  LAYER NO  1

  X=        0.00        0.00
  Y=        0.00        5.98

NORMAL STRESSES
SXX    -.2847E+03 -.2121E+03
SYY    -.2847E+03 -.1335E+03
SZZ    -.8000E+02 -.4126E+02

SHEAR STRESSES
SXY    0.          0.
SXZ    0.          0.
SYZ    0.          -.3626E-11

PRINCIPAL STRESSES
PS 1   -.8000E+02 -.4126E+02
PS 2   -.2847E+03 -.1935E+03
PS 3   -.2847E+03 -.2121E+03

PRINCIPAL SHEAR STRESSES
PSS 1   .1024E+03  .8542E+02
PSS 2   .1024E+03  .7114E+02
PSS 3 0.           .1428E+02

DISPLACEMENTS
UX      0.          0.
UY      0.          -.2435E-02
UZ       .6032E-01  .5655E-01

NORMAL STRAINS
EXX    -.4628E-03 -.4073E-03
EYY    -.4628E-03 -.2740E-03
EZZ     .4926E-03  .3900E-03

SHEAR STRAINS
EXY    0.          0.
EXZ    0.          0.
EYZ    0.          -.3385E-16

PRINCIPAL STRAINS
PE 1    .4926E-03  .3900E-03
PE 2   -.4628E-03 -.2740E-03
PE 3   -.4628E-03 -.4073E-03

PRINCIPAL SHEAR STRAINS
PSE 1  .9555E-03  .7972E-03
PSE 2  .9555E-03  .6539E-03
PSE 3 0.          .1333E-03
```

Figure 13b  Output for Example Problem (ELSYM5)

```
1*************** TRIAL RUN PSAD2A  R.D. HICKS  10-14-81                                   ***************        PAGE  1
0                                THE PROBLEM PARMETERS ARE,
0                             TOTAL LOAD PER WHEEL   9000.00  LBS
0                             TIRE PRESSURE..          80.00  PSI
0                             LOAD RADIUS..             5.98  IN.

 LAYER  1  HAS MODULUS   300000.  FROM  300000.0  THETA **    0.000  POISSONS RATIO  .400  THICKNESS  1.5  IN.  UNIT.WT. 150.0 PCF
 LAYER  2  HAS MODULUS   300000.  FROM  300030.0  THETA **    0.000  POISSONS RATIO  .400  THICKNESS  1.5  IN.  UNIT.WT. 150.0 PCF
 LAYER  3  HAS MODULUS   300000.  FROM  300000.0  THETA **    0.000  POISSONS RATIO  .400  THICKNESS  1.5  IN.  UNIT.WT. 150.0 PCF
 LAYER  4  HAS MODULUS   300000.  FROM  300000.0  THETA **    0.000  POISSONS RATIO  .400  THICKNESS  1.5  IN.  UNIT.WT. 150.0 PCF
 LAYER  5  HAS MODULUS     3000.  FROM DEVIATOR STRESS RELATIONSHIP  POISSONS RATIO  .400  AND IS SEMI-INFINITE
0
```

| | | STRESSES | | | | | DISPLACEMENT | STRAINS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R | Z | VERTICAL | TANGENTIAL | RADIAL | SHEAR | BULK | VERTICAL | RADIAL | TANGENTIAL | VERTICAL | |
| 0.00 | 0.00 | -8.000E+01 | -2.847E+02 | -2.847E+02 | 0. | -6.495E+02 * | 6.032E-02 * | -4.628E-04 | -4.628E-04 | 4.926E-04 | |
| 0.00 | -1.50 | -7.014E+01 | -1.398E+02 | -1.398E+02 | 0. | -3.498E+02 * | 6.078E-02 * | -1.861E-04 | -1.861E-04 | 1.391E-04 | SLOW |
| 0.00 | 1.50 | -7.014E+01 | -1.398E+02 | -1.398E+02 | 0. | -3.498E+02 * | 6.078E-02 * | -1.861E-04 | -1.861E-04 | 1.391E-04 | |
| 0.00 | 2.25 | -5.930E+01 | -7.436E+01 | -7.436E+01 | 0. | -2.080E+02 * | 6.083E-02 * | -6.966E-05 | -6.966E-05 | 6.329E-07 | |
| 0.00 | -3.00 | -4.617E+01 | -1.153E+01 | -1.153E+01 | 0. | -6.934E+01 * | 6.078E-02 * | 3.840E-05 | 3.840E-05 | -1.230E-04 | |
| 0.00 | 3.00 | -4.617E+01 | -1.158E+01 | -1.158E+01 | 0. | -6.934E+01 * | 6.078E-02 * | 3.840E-05 | 3.840E-05 | -1.230E-04 | |
| 0.00 | 3.75 | -3.240E+01 | 5.042E+01 | 5.042E+01 | 0. | 6.843E+01 * | 6.064E-02 * | 1.440E-04 | 1.446E-04 | -2.425E-04 | |
| 0.00 | -4.50 | -1.986E+01 | 1.138E+02 | 1.138E+02 | 0. | 2.078E+02 * | 6.042E-02 * | 2.542E-04 | 2.542E-04 | -3.698E-04 | |
| 0.00 | 4.50 | -1.986E+01 | 1.133E+02 | 1.134E+02 | 0. | 2.078E+02 * | 6.042E-02 * | 2.542E-04 | 2.542E-04 | -3.698E-04 | |
| 0.00 | 5.25 | -1.059E+01 | 1.811E+02 | 1.811E+02 | 0. | 3.517E+02 * | 6.008E-02 * | 3.764E-04 | 3.764E-04 | -5.183E-04 | |
| 0.00 | -6.00 | -6.766E+00 | 2.549E+02 | 2.549E+02 | 0. | 5.031E+02 * | 5.963E-02 * | 5.189E-04 | 5.189E-04 | -7.024E-04 | |
| 0.00 | 6.00 | -6.766E+00 | -1.917E+00 | -1.917E+00 | 0. | -1.060E+01 * | 5.963E-02 * | 5.189E-04 | 5.189E-04 | -1.744E-03 | |
| 5.98 | 0.00 | -4.000E+01 | -2.110E+02 | -1.822E+02 | 4.899E-13 | -4.332E+02 * | 5.652E-02 * | -2.727E-04 | -4.072E-04 | 3.910E-04 | |
| 5.98 | -1.50 | -3.295E+01 | -9.732E+01 | -9.525E+01 | -4.517E+01 | -2.255E+02 * | 5.692E-02 * | -1.438E-04 | -1.535E-04 | 1.469E-04 | SLOW |
| 5.98 | 1.50 | -3.295E+01 | -9.732E+01 | -9.525E+01 | -4.517E+01 | -2.255E+02 * | 5.692E-02 * | -1.438E-04 | -1.535E-04 | 1.469E-04 | |
| 5.98 | 2.25 | -2.750E+01 | -4.929E+01 | -5.291E+01 | -4.833E+01 | -1.297E+02 * | 5.699E-02 * | -7.399E-05 | -5.709E-05 | 4.462E-05 | |
| 5.98 | -3.00 | -2.157E+01 | -3.215E+00 | -1.111E+01 | -4.770E+01 | -3.589E+01 * | 5.698E-02 * | -3.978E-06 | 3.285E-05 | -5.280E-05 | |
| 5.98 | 3.00 | -2.157E+01 | -3.215E+00 | -1.111E+01 | -4.770E+01 | -3.589E+01 * | 5.698E-02 * | -3.978E-06 | 3.285E-05 | -5.280E-05 | |
| 5.98 | 3.75 | -1.577E+01 | 4.246E+01 | 3.054E+01 | -4.329E+01 | 5.724E+01 * | 5.691E-02 * | 6.621E-05 | 1.219E-04 | -1.499E-04 | |
| 5.98 | -4.50 | -1.071E+01 | 8.916E+01 | 7.243E+01 | -3.472E+01 | 1.509E+02 * | 5.676E-02 * | 1.368E-04 | 2.149E-04 | -2.512E-04 | |
| 5.98 | 4.50 | -1.071E+01 | 8.916E+01 | 7.243E+01 | -3.472E+01 | 1.509E+02 * | 5.676E-02 * | 1.368E-04 | 2.149E-04 | -2.512E-04 | |
| 5.98 | 5.25 | -7.051E+00 | 1.383E+02 | 1.149E+02 | -2.115E+01 | 2.462E+02 * | 5.653E-02 * | 2.081E-04 | 3.172E-04 | -3.612E-04 | |
| 5.98 | -6.00 | -5.525E+00 | 1.916E+02 | 1.583E+02 | -1.062E+00 | 3.444E+02 * | 5.621E-02 * | 2.798E-04 | 4.346E-04 | -4.849E-04 | |
| 5.98 | 6.00 | -5.525E+00 | -1.731E+00 | -2.063E+00 | -1.062E+00 | -9.318E+00 * | 5.621E-02 * | 2.798E-04 | 4.348E-04 | -1.336E-03 | |
| 8.98 | 0.00 | -2.274E-01 | -1.382E+02 | -9.613E+01 | 4.570E-13 | -2.345E+02 * | 5.302E-02 * | -1.359E-04 | -3.326E-04 | 3.116E-04 | |
| 8.98 | -1.50 | -3.153E-01 | -6.761E+01 | -5.756E+01 | -2.387E+01 | -1.255E+02 * | 5.338E-02 * | -1.013E-04 | -1.482E-04 | 1.658E-04 | SLOW |
| 8.98 | 1.50 | -3.153E-01 | -6.761E+01 | -5.756E+01 | -2.387E+01 | -1.255E+02 * | 5.338E-02 * | -1.013E-04 | -1.482E-04 | 1.658E-04 | |
| 8.98 | 2.25 | -1.171E+00 | -3.392E+01 | -3.441E+01 | -3.089E+01 | -6.950E+01 * | 5.348E-02 * | -6.790E-05 | -6.563E-05 | 8.728E-05 | |
| 8.98 | -3.00 | -2.170E+00 | -5.357E-01 | -9.420E+00 | -3.376E+01 | -1.213E+01 * | 5.351E-02 * | -2.779E-05 | 1.367E-05 | 6.041E-06 | |
| 8.98 | 3.00 | -2.170E+00 | -5.357E-01 | -9.420E+00 | -3.376E+01 | -1.213E+01 * | 5.351E-02 * | -2.779E-05 | 1.367E-05 | 6.041E-06 | |
| 8.98 | 3.75 | -3.067E+00 | 3.300E+01 | 1.635E+01 | -3.233E+01 | 4.628E+01 * | 5.349E-02 * | 1.457E-05 | 9.231E-05 | -7.602E-05 | |
| 8.98 | -4.50 | -3.781E+00 | 6.717E+01 | 4.194E+01 | -2.653E+01 | 1.053E+02 * | 5.340E-02 * | 5.528E-05 | 1.730E-04 | -1.581E-04 | |
| 8.98 | 4.50 | -3.781E+00 | 6.717E+01 | 4.194E+01 | -2.653E+01 | 1.053E+02 * | 5.340E-02 * | 5.528E-05 | 1.730E-04 | -1.581E-04 | |
| 8.98 | 5.25 | -4.296E+00 | 1.024E+02 | 6.643E+01 | -1.622E+01 | 1.646E+02 * | 5.325E-02 * | 9.859E-05 | 2.586E-04 | -2.395E-04 | |
| 8.98 | -6.00 | -4.483E+00 | 1.393E+02 | 8.869E+01 | -1.112E+00 | 2.235E+02 * | 5.304E-02 * | 1.159E-04 | 3.520E-04 | -3.189E-04 | |
| 8.98 | 6.00 | -4.483E+00 | -1.566E+00 | -2.072E+00 | -1.112E+00 | -8.121E+00 * | 5.304E-02 * | 1.159E-04 | 3.520E-04 | -1.089E-03 | |

Figure 13c. Output for Example Problem (PSAD2A)

```
                                          POSITION NUMBER  1

                                            LAYER NUMBER   1

                                             COORDINATES

                                    X              Y              Z
                                0.            C.            0.

                DISTANCE TO LOAD-AXIS( 1)                                    THETA
                      0.                                                     0.

DISPLACEMENTS
   RADIAL              TANGENTIAL              VERTICAL
 0.                      0.                     .6046E-01
   STRESSES
   RADIAL              TANGENTIAL              VERTICAL          RAD./TANG.          RAD./VERT.          TANG./VERT.
 -.2838E+03              -.2838E+03            -.8000E+02
   STRAINS
   RADIAL              TANGENTIAL              VERTICAL          RAD./TANG.          RAD./VERT.          TANG./VERT.
 -.4610E-03              -.4610E-03             .4902E-03

                              XX            YY            ZZ            YZ          XZ          XY          UX          UY          UZ
T O T A L   S T R E S S    -.284E+03     -.284E+03     -.800E+02                              0.
T O T A L   S T R A I N    -.461E-03     -.461E-03      .490E-03                              0.
T O T A L   D I S P L A C E M E N T                                                                       0.          0.       .605E-01
```

Figure 13d. Output for Example Problem (BISAR) by Cartesian coordinates. Shell BISAR has the capability of computing the stresses shown in Table 1, and outputs each for all positions shown as Cartesian points along with a summary of total stresses.

2. Strains. Radial, tangential, and vertical strains are calculated by PSAD2A and the CHEV5L programs; ELSYM5 outputs the same components of strain as it does of shear for each position requested; and BISAR computes and outputs those strains requested from the list in Table 1, besides giving a summary of total strains.

3. Displacements. ELSYM5 and BISAR each compute three displacements, but present them in a slightly different manner. ELSYM5 displays displacements in a three-dimensional Cartesian coordinate system context, while BISAR displays them not as horizontal, vertical, and normal displacements, but as radial, tangential, and vertical displacements. PSAD2A, CHEV5L, and CHEV5L w/iteration show only vertical deflection.

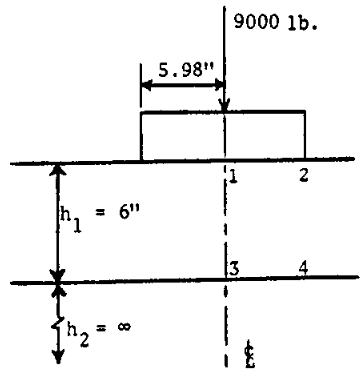
4. Wheel Load Considerations. The output shown in Fig. 13 is for one uniformly applied vertical load. The load and contact pressure are input data. These data together with the calculated load radius are printed in the output. All multiple wheel considerations in the Chevron programs must be handled by superposition (see next section). The other three programs, ELSYM5, BISAR, and PSAD2A permit the use of two or more wheels.

5. Sign Notation. A negative sign implies compression when indicated as a stress or strain. Positive, of course, would imply tension. A negative sign for depth implies that the stresses are calculated in the upper layer while a positive sign means the calculation is in the lower layer. This latter notation occurs only at a layer interface.

The data given in Fig. 13 were also used to develop Table 2 for comparing results from the various programs. Note that all critical values are essentially the same: both signs and magnitudes agree.

An attempt to compare computational efficiency was made by including CPU time for each run. CPU time refers to central processing unit time, or the seconds during which the computer was actually working on the problem. On

Table 2. Comparison of Results From Different Programs




VERTICAL STRESS (PSI)

| POSITION | ELSYM5 | PSAD2A | CHEV5L | CHEV5L w/Iter. | BISAR |
|---|---|---|---|---|---|
| 1 | -80.0 | -80.0 | -80.0 | -80.0 | -80.1 |
| 2 | -41.3 | -40.0 | -41.3 | -41.3 | -40.1 |
| 3 | - 6.8 | - 6.8 | - 6.8 | - 6.8 | - 6.7 |
| 4 | - 5.5 | - 5.5 | - 5.5 | - 5.5 | - 5.5 |

VERTICAL STRAIN (in/in x $10^{-4}$)

| POSITION | ELSYM5 | PSAD2A | CHEV5L | CHEV5L w/Iter. | BISAR |
|---|---|---|---|---|---|
| 1 | 4.9 | 4.9 | | | 4.9 |
| 2 | 3.9 | 3.9 | | | 3.9 |
| 3 | - 7.0 | - 7.0 | | | - 7.0 |
| 4 | - 4.9 | - 4.8 | | | - 4.8 |

TANGENTIAL STRESS (PSI)

| POSITION | ELSYM5 | PSAD2A | CHEV5L | CHEV5L w/Iter. | BISAR |
|---|---|---|---|---|---|
| 1 | -284.7 | -284.7 | -284.7 | -284.7 | -284.0 |
| 2 | -212.1 | -211.0 | -212.1 | -212.1 | -210.3 |
| 3 | 254.9 | 254.9 | 254.9 | 254.9 | 254.2 |
| 4 | 191.6 | 191.6 | 191.6 | 191.6 | 190.8 |

TANGENTIAL STRAIN (in/in x $10^{-4}$)

| POSITION | ELSYM5 | PSAD2A | CHEV5L | CHEV5L w/Iter. | BISAR |
|---|---|---|---|---|---|
| 1 | - 4.6 | - 4.6 | - 4.6 | - 4.6 | - 4.6 |
| 2 | - 4.1 | - 4.1 | - 4.1 | - 4.1 | - 4.1 |
| 3 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 |
| 4 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 |

RADIAL STRESS (PSI)

| POSITION | ELSYM5 | PSAD2A | CHEV5L | CHEV5L w/Iter. | BISAR |
|---|---|---|---|---|---|
| 1 | -284.7 | -284.7 | -284.7 | -284.7 | -284.0 |
| 2 | -183.5 | -182.2 | -183.5 | -183.5 | -181.3 |
| 3 | 254.9 | 254.9 | 254.9 | 254.9 | 254.2 |
| 4 | 158.5 | 158.3 | 158.5 | 158.5 | 157.6 |

RADIAL STRAIN (in/in x $10^{-4}$)

| POSITION | ELSYM5 | PSAD2A | CHEV5L | CHEV5L w/Iter. | BISAR |
|---|---|---|---|---|---|
| 1 | - 4.6 | - 4.6 | - 4.6 | - 4.6 | - 4.6 |
| 2 | - 2.7 | - 2.7 | - 2.7 | - 2.7 | - 2.7 |
| 3 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 |
| 4 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |

CPU TIME (SEC.)*

| | ELSYM5 | PSAD2A | CHEV5L | CHEV5L w/Iter. | BISAR |
|---|---|---|---|---|---|
| | 1.762 | 15.165 | 1.761 | 28.239 | 2.606 |

* Run on CDC CYBER 73/74

the basis of this, a ranking of efficiency is ELSYM5, CHEV5L, BISAR, PSAD2A and CHEV5L w/iteration.

MULTIPLE GEAR CONSIDERATIONS

For the Chevron programs (CHEV5L and CHEV5L w/Iteration), output is given for only one circular load. Unfortunately, most vehicles for which pavements are to be designed have either dual or dual-tandem wheel configurations (Fig. 14). The question arises, therefore, of how does one determine the critical stresses or deformations for realistic wheel load configurations? The answer, use of the principle of superposition. This can best be illustrated through an example using the output information presented in Fig. 13.

Let us consider the dual wheel configuration. The principle is also applicable to multiple wheel cases and is described as follows:

1) Deformations. The most important deformation one calculates is surface deformation. To calculate the maximum surface deformation resulting from dual wheels one would add the contribution of a second wheel to that of the first. The surface deflection under the first wheel (R=0,Z=0) equals .060 inch (from Fig. 15a) while that due to the second wheel (R=18.0,Z=0) displaced 18 inches from the first is .042 inch. The total deflection under the first wheel equals the total of both tires or .102 inch. The surface deflection at the edge of one of the dual tires (Fig. 15a) would equal $\Delta_2$, which is the sum of $\Delta_{21}$ and $\Delta_{25}$. From Fig. 13a, $\Delta_{21}$(R=6.0",Z=0) = .057", and $\Delta_{25}$(R=12.0",Z=0) = .049". Thus, $\Delta_2$ = 0.106". Surface deflections at other intermediate points would be calculated in a similar fashion to determine the maximum value.

2) Stresses and Strains. These two responses would be handled in a similar fashion. Further, the maximum stress and/or strain usually occurs under one of the dual tires. What is needed is to convert the cylindrical coordinates (radial and tangential) to Cartesian coordinates (longitudinal and transverse). Under the first wheel the radial ($\sigma_{r_1}$) and tangential ($\sigma_{t_1}$) stresses are identical. However, the stresses ($\sigma_{r_2}$, $\sigma_{t_2}$) at the first wheel due to the

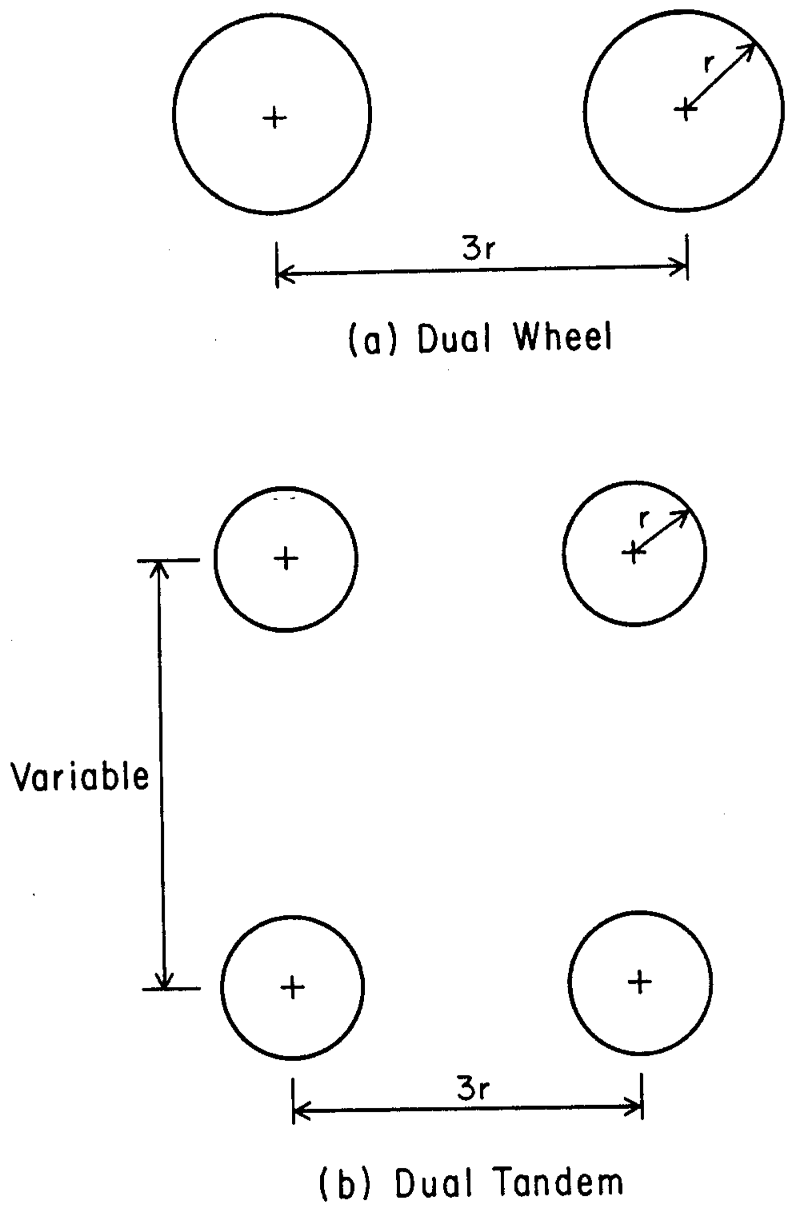



Figure 14. Typical Wheel Configurations
(Plan View)

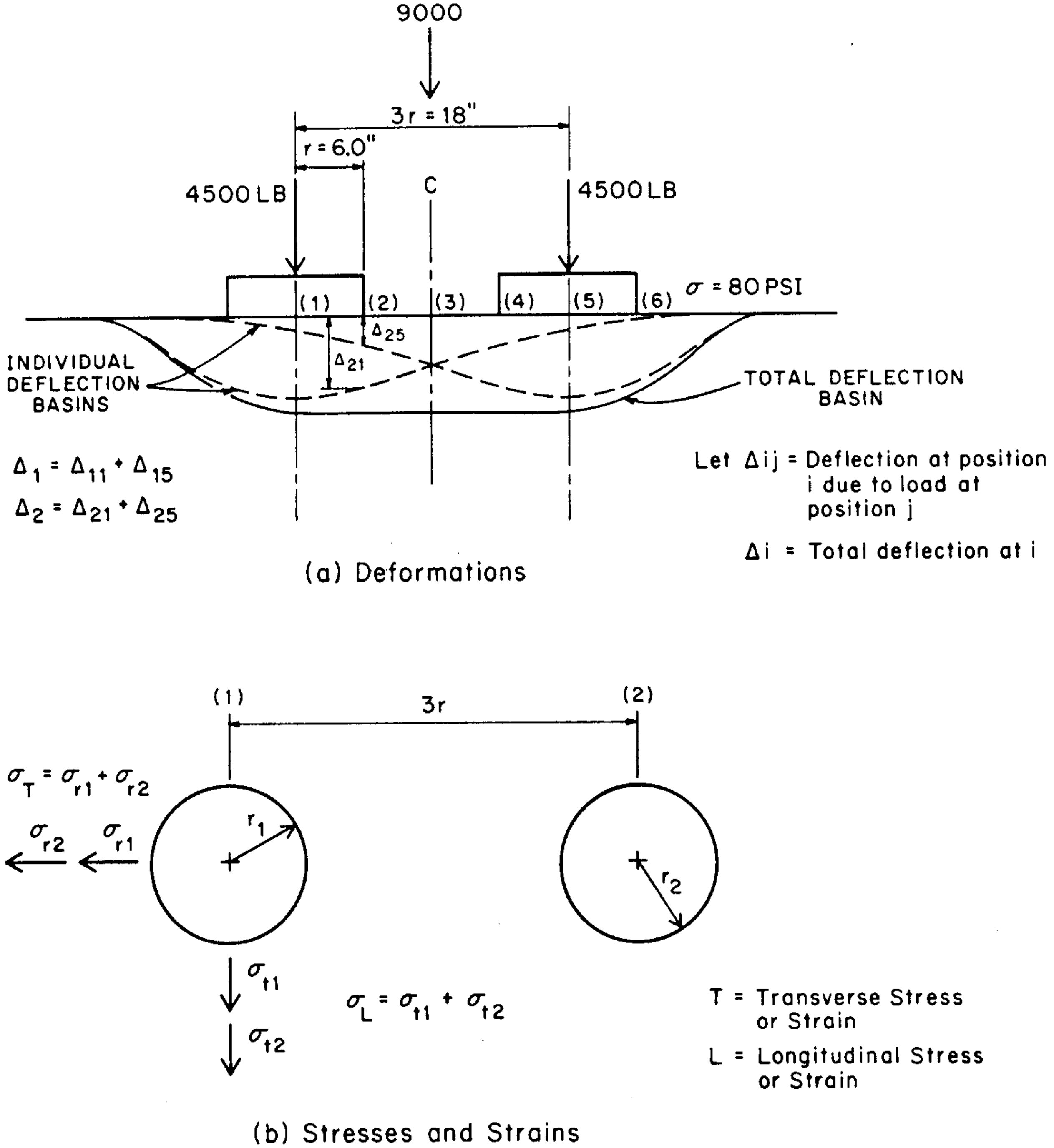



Figure 15. Example of Principle of Superposition for Dual Wheels

second wheel (displaced a distance 3 radii, R=18.0, Z=0.0) are different. Figure 15b shows how they can be added to give the longitudinal and transverse stress conditions. Under most conditions, only the critical stress (or strain) is of interest and this usually occurs at the bottom of the stabilized layer.

For dual-tandem wheel configuration the basic principles described above can also be used. The principal advantage of the Shell BISAR and ELSYM5 programs is that they can accommodate multiple wheel configurations automatically. PSAD2A considers dual wheels automatically.

## POTENTIAL APPLICATIONS

The question often arises as to the purpose for using layered theory in the design and evaluation of pavement systems. This is particularly so when several presently used pavement design procedures (e.g. AASHO, California, etc.) appear to be very sound. However, many decisions were made in their development (because of lack of necessary tools or better information) that invalidate extrapolation of present design procedures to conditions different from that for which they were developed.

In recent years, considerable emphasis has been placed on the development of a more mechanistic design procedure, one which would allow extrapolation to any set of design conditions. This is particularly important because of ever increasing wheel loads such as those from off highway vehicles. Layered theory analysis uses actual load data and fundamental material properties and can properly account for rapidly changing design conditions. This does not mean, however, that layered theory analysis will be a practical design tool, because input to the design process requires sophisticated materials testing and computational equipment. What it does mean is that layered analysis techniques can provide the necessary tools to understand and account for:

1) The impact of increased loads on the performance of the pavement system.
2) An evaluation of realistic layer equivalencies for structural materials heretofore not used (e.g., marginal).
3) Verification or modification of load equivalencies in the design of pavement systems and in the assignment of maintenance responsibilities in the case of dual ownership.

In specific, the following applications are recommended for each of the five programs described in Chapter Three:

1) CHEV5L. This program is the simplest to operate. It should always be considered first to give a "ball park" solution to a particular problem. The most significant limitation is its inability to handle nonlinear material problems. Therefore, its use should probably be limited to full-depth asphalt pavements over subgrade.
2) CHEV5L w/Iteration. This program is slower than CHEV5L but does allow one to account for nonlinear material behavior. This program should be used where a considerable amount of untreated aggregate is present (e.g. unsurfaced roads).
3) SHELL BISAR. This program, because of its multiple gear option, would be most useful in the evaluation of off-highway loads. Further, the additional capability of horizontal stresses and ability to vary friction between layers offer capabilities which none of the others can. However, computational experience of the author with the horizontal stress option indicates that excessive time may be used by the computer to converge to a solution. This option should be used only with extreme caution.
4) ELSYM5. This program, similar to the SHELL BISAR model, was found to be the most efficient in terms of computer time. Applications for ELSYM5 are similar to those of BISAR since multiple loads can be considered.
5) PSAD2A. While akin to CHEV5L w/iteration, PSAD2A allows evaluation of stresses, strains and displacements due to a dual wheel load configuration, such as is shown in Fig. 15a. PSAD2A has the capability of handling nonlinear material behavior; in this way it is similar to CHEV5L w/iteration.

These five programs (or their equivalent) should provide pavement designers with the necessary tools to evaluate almost any unusual design situation.

# CHAPTER FIVE

## SUMMARY AND RECOMMENDATIONS

This report has presented in simple terms a description of layered elastic analyses and five computer programs which solve the fundamental differential equations. Further, the potential use of layered elastic analysis in the design and evaluation of highway pavements has been discussed.

It is recommended that highway engineers utilize the computer programs to assist in various decision making processes such as:

1) Establishing more realistic load equivalencies;
2) Evaluation of the impact of increased loads on the highway system;
3) Evaluation of the use of marginal materials as replacements for quality materials;
4) Evaluation of overlay requirements.

There may be many other potential applications. The uses of layered analyses are numerous and the benefits from its use could be considerable.

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# APPENDIX A

## INPUT FORMATS

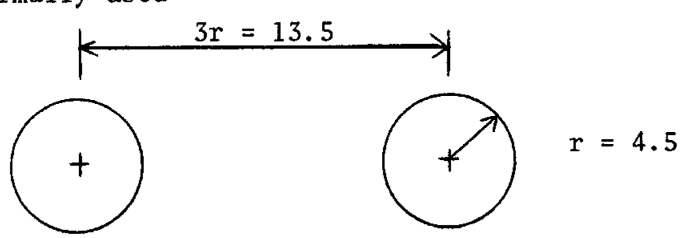
This Appendix presents the input format requirements for CHEV5L, CHEV5L w/Iteration, SHELL BISAR, ELSYM5 and PSAD2A.

The notation CC refers to card columns, with the range of columns being inclusive. All "Real" values (REAL) are punched with a decimal point as a part of the value and all "integer" values (INTEGER) are to be punched without a decimal point. Both real and integer values must be right justified in the data field. The required load input will always be the load carried by one wheel in any type of tire configuration.

CHEV5L

| | | | |
|---|---|---|---|
| 1) | CC 1-72 | any combination of alphameric characters may be used to identify the program. | (ALPHA) |
| | | FORMAT (A72) | |
| 2) | CC 1-12 | total load in pounds, | (REAL) |
| | CC13-24 | unit contact pressure in psi, | (REAL) |
| | | FORMAT (2F12.0) | |
| 3) | CC 1-2 | number of layers in the system, | (INTEGER) |
| | CC 3-10 | modulus of elasticity (psi) for layer 1, | (REAL) |
| | CC11-16 | Poisson's ratio for layer 1, | (REAL) |
| | CC17-72 | Modulus (psi) and Poisson's ratio for layers 2 through 5. | (REAL) |
| | | FORMAT (I2,5(F8.0,F6.0)) | |
| 4) | CC 1- 6 | thickness of layer 1 in inches, | (REAL) |
| | CC 7-24 | thickness of layers 2 through 4. | (REAL) |
| | | FORMAT (4F6.0) | |
| 5) | CC 1- 6 | number of radial (R) values for which calculations are needed, | (INTEGER) |

For dual wheels the following configuration is normally used




Therefore R values selected include 0, 4.5, 6.7, 9.0, 13.5, 18.0

| | | |
|---|---|---|
| CC 7-12 | first R value, | (REAL) |
| CC13-18, | 19-24, 25-30 second, third, etc., R value, | (REAL) |
| | FORMAT (I6,11F6.0) | |

| | | | |
|---|---|---|---|
| 6) | CC 1- 6 | number of depth (Z) values on card, | (INTEGER) |
| | CC 7-12 | first Z value, | (REAL) |
| | CC13-18, | 19-24, 25-30, second, third, etc., Z value. | (REAL) |
| | | FORMAT (I6,11F6.0) | |

Cards 1 through 6 may be repeated for each different system to be solved.

**IBM** FORTRAN Coding Form GX28-7327-6 U/M 050** Printed in U.S.A.

PROGRAM: INPUT FORMAT - CHEV5L

PROGRAMMER: DATE: PUNCHING INSTRUCTIONS: GRAPHIC / PUNCH PAGE OF CARD ELECTRO NUMBER*

| | | |
|---|---|---|
| 1 | IDENTIFICATION | FORMAT(12A6) |
| 2 | WEIGHT / PRESSURE | FORMAT(2F12.0) |
| 3 | NO. / E(I) / V(I) / ... / ... | FORMAT(I2,5(F8.0,F6.0)) |
| 4 | H(1) / H(2) / H(3) / H(4) | FORMAT(4F6.0) |
| 5 | NO. R / R(1) / R(2) / ... | FORMAT(I6,11F6.0) |
| 6 | NO. Z / Z(1) / Z(2) / ... | FORMAT(I6,11F6.0) |

*A standard card form, IBM electro 888157, is available for punching statements from this form

**Number of forms per pad may vary slightly

Figure A-1 Input Format - CHEV5L

CHEV5L - ITERATION - PSAD

| | | | |
|---|---|---|---|
| 1) | CC 1- 5 | number of pavement systems to be solved. | (INTEGER) |
| | | FORMAT (I5) | |
| 2) | CC 1-72 | any combination of alphameric characters may be used to identify the problem to be solved. | (ALPHA) |
| | | FORMAT (8A10) | |
| 3) | CC 1-12 | total wheel load in pounds, | (REAL) |
| | CC13-24 | unit pressure in psi, | (REAL) |
| | CC25-36 | absolute or relative output data selector - normally zero, | (INTEGER) |
| | CC37-40 | number of layers above subgrade requiring iteration, | (INTEGER) |
| | CC41-44 | problem identification: | (INTEGER) |
| | | 1 - One stress calculation (Same as CHEV5L)<br>2 - Iterate as indicated. | |
| | | FORMAT (2F12.0,I12,I4,I5) | |
| 4) | CC 1- 2 | number of layers in the system, | (INTEGER) |
| | CC 3-10 | initially assumed modulus of elasticity (psi) for layer 1, | (REAL) |
| | CC11-16 | Poisson's ratio for layer 1, | (REAL) |
| | CC17-72 | Modulus (psi) and Poisson's ratio for layers 2 through 5. | (REAL) |
| | | FORMAT (I2,5(F8.0,6.0)) | |
| 5) | CC 1-10 | the coefficient $\bar{k}$ in the equation $M_R = \bar{k}\theta^{\bar{n}}$ for layer 1, | (REAL) |
| | CC11-20 | the exponent $\bar{n}$ for layer 1, | (REAL) |
| | CC21-80 | coefficient $\bar{k}$ and exponent $\bar{n}$ for layers 2 through 4. | (REAL) |
| | | FORMAT (8F10.0) | |

| | | | |
|---|---|---|---|
| 6) | CC 1-10 | unit weight (pcf) of layer 1, | (REAL) |
| | CC11-40 | unit weight (pcf) of layers 2 through 4. | (REAL) |
| | | FORMAT (4F10.0) | |
| 7) | | Subgrade properties | |
| | CC 1- 2 | the number of points necessary to establish the $\sigma_d$ vs $M_R$ relationship of the subgrade, | (INTEGER) |
| | CC 3- 8 | Initial Deviator Stress, must equal zero for first point, | (REAL) |
| | CC 9-16 | Resilient Modulus at previous deviator stress. | (REAL) |
| | | FORMAT (I2,F6.0, 9F8.0/10F8.0) | |
| | | Note: This format allows for the use of 10 points maximum. This first is in field (F6.0,F8.0), the next four are in the fields (8F8.0) and the last five are on another card (10F8.0). | |
| 8) | CC 1- 6 | thickness of layer 1 in inches, | (REAL) |
| | CC 7-24 | thicknesses of layers 2 through 4. | (REAL) |
| | | FORMAT (4F6.0) | |
| 9) | CC 1- 6 | number of R (radius) values on card, | (INTEGER) |
| | CC 7-12 | first R value, | (REAL) |
| | CC13-18, | 19-24, 25-30 second, third, etc. R value, | |
| | | FORMAT (I6,11F6.0) | |
| 10) | CC 1- 6 | number of Z (depth) values on card, | (INTEGER) |
| | CC 7-12 | first Z value, | (REAL) |
| | CC13-18, | 19-24, 25-30 second, third, etc., Z value. | (REAL) |
| | | FORMAT (I6,11F6.0) | |

Cards number 2 through 10 are repeated for each different system to be solved.

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Printed in U.S.A.

PROGRAM: INPUT FORMAT - CHEV5L WITH ITERATION

PROGRAMMER | DATE | PUNCHING INSTRUCTIONS | GRAPHIC | PUNCH | PAGE OF | CARD ELECTRO NUMBER*

| Card | C | STATEMENT NUMBER | CONT | FORTRAN STATEMENT | IDENTIFICATION SEQUENCE |
|---|---|---|---|---|---|
| 1 | | | | FORMAT(I5) #OF SYSTEMS TO BE SOLVED | |
| 2 | | | | IDENTIFICATION | FORMAT(8A10) |
| 3 | | | | WEIGHT \| PRESSURE \| ABSOLUTE/RELATIVE \| # OF LAYERS REQUIRING ITERATION \| OPTION FORMAT(2F12.Ø, I12, I4, I5) | |
| 4 | | NQ | | E(1) \| V(1) \| • • • \| • • • FORMAT(I2,5(F8.Ø,6.Ø)) | |
| 5 | | | | FRONT(1) \| POWER(1) \| • • • \| • • • FORMAT(8F1Ø.Ø) | |
| 6 | | | | UNIT WEIGHT(1) \| • • • \| • • • \| • • • FORMAT(4F1Ø.Ø) | |
| 7 | | NQ | | DEV(1) \| RMOD(1) \| • • • \| • • • FORMAT(I2,F6.Ø,9F8.Ø/1ØF8.Ø) | |
| 8 | | | | H(1) \| • • • \| • • • \| • • • FORMAT(4F6.Ø) | |
| 9 | | NO. R | | R(1) \| • • • FORMAT(I6,11F6.Ø) | |
| 10 | | NO. Z | | Z(1) \| • • • FORMAT(I6,11F6.Ø) | |

*A standard card form, IBM electro 888157, is available for punching statements from this form

**Number of forms per pad may vary slightly

Figure A-2 Input Format - CHEV5L with Iteration

## SHELL BISAR*

| | | | |
|---|---|---|---|
| 1) | CC 1-60 | TEXT - identification of the program. | (ALPHA) |
| | CC61-70 | DATE - date of computer run. | (INTEGER) |
| | | FORMAT (15A4,I2,I3,I5) | |
| 2) | CC 1- 2 | NSYS - number of systems. | (INTEGER) |
| | | FORMAT (I2) | |
| 3) | CC 1- 2 | NLAYS - number of layers, including subgrade, | (INTEGER) |
| | CC 3- 5 | [ISMO] - OPTIONAL | (INTEGER) |
| | | If ISMO = 1, program will print smooth if SLIP is greater than 100, and rough if less than 100. | |
| | | FORMAT (I2,[I3]) | |
| 4) | CC 1-12 | E(1) - modulus of elasticity of the layer in stress units, | (REAL) |
| | CC13-24 | NU(1) - Poisson's ratio of the layer, | (REAL) |
| | CC25-36 | THICK(1) - thickness of the layer in length units, | (REAL) |
| | CC37-48 | [SLIP(1)] - OPTIONAL (used with ISMO option), where | (REAL) |

SLIP(1) = 0, complete adhesion ) Values of SLIP between 0
) and 1000 will yield varying
SLIP(1) = $10^3$, frictionless slip ) degrees of slip.

FORMAT (3E12.6,[E12.6])

Note: Card 4 is repeated (to a maximum of 8 times) for each following layer, with the exception of the bottom layer, for which the next card is used.

| | | | |
|---|---|---|---|
| 5) | CC 1-12 | E(3) - modulus of elasticity of bottom layer, | (REAL) |
| | CC13-24 | NU(3) - Poisson's ratio of bottom layer, | (REAL) |
| | | FORMAT (2E12.6) | |
| 6) | CC 1- 2 | NLOAD - number of loads, | INTEGER) |
| | | FORMAT (I2) | |

* Either English or SI units can be used with BISAR.

| | | | |
|---|---|---|---|
| 7) | CC 1-4 | IDENT(1) - LOAD or STRS according to the units in which the load is expressed: units of load or units of load stress, | (ALPHA) |
| | CC 7-18 | LDSTRS(1) - vertical load in load or stress units, | (REAL) |
| | CC19-30 | RADIUS(1) - radius of loaded area in length units, | (REAL) |
| | CC31-42 | X(1) - abscissa of position of load in length units, | (REAL) |
| | CC43-54 | Y(1) - ordinate of position of load in length units, | (REAL) |
| | CC55-66 | HOSTR(1) - horizontal load in load or stress units, | (REAL) |
| | CC67-78 | PSI(1) - angle of HOSTR(1) with respect to the positive x-axis in degrees**. | (REAL) |

FORMAT (A4,2X,6E12.6)

Note: Card 7 is repeated (to a maximum of 9 times) for each wheel load.

| | | | |
|---|---|---|---|
| 8) | CC 1- 3 | REQEST(1) - URb* if radial displacement $U_r$ is required, bbb if not, | (ALPHA) |
| | CC 4- 6 | REQEST(2) - UTb if tangential displacement $U_t$ is required, bbb if not, | (ALPHA) |
| | CC 7- 9 | REQEST(3) - UZb if vertical displacement $U_z$ is required, bbb if not, | (ALPHA) |
| | CC10-12 | REQEST(4) - SRR if radial stress $\sigma_{rr}$ is required, bbb if not, | (ALPHA) |
| | CC13-15 | REQEST(5) - STT if tangential stress $\sigma_{tt}$ is required, bbb if not, | (ALPHA) |
| | CC16-18 | REQEST(6) - SZZ if vertical stress $\sigma_{zz}$ is required, bbb if not, | (ALPHA) |
| | CC19-21 | REQEST(7) - SRT if radial/tangential stress $\sigma_{rt}$ is required, bbb if not, | (ALPHA) |

* b means blank
** Use 0° or 90°, braking would be 90°. Angles are printed out in radians.

| | | | |
|---|---|---|---|
| CC22-24 | REQEST(8) | - SRZ if radial/vertical stress $\sigma_{rz}$ is required, bbb if not, | (ALPHA) |
| CC25-27 | REQEST(9) | - STZ if tangential/vertical stress $\sigma_{tz}$ is required, bbb if not, | (ALPHA) |
| CC28-30 | REQEST(10) | - ERR if radial strain $\varepsilon_{rr}$ is required, bbb if not, | (ALPHA) |
| CC31-33 | REQEST(11) | - ETT if tangential strain $\varepsilon_{tt}$ is required, bbb if not, | (ALPHA) |
| CC34-36 | REQEST(12) | - EZZ if vertical strain $\varepsilon_{zz}$ is required, bbb if not, | (ALPHA) |
| CC37-39 | REQEST(13) | - ERT if radial/tangential strain $\varepsilon_{rt}$ is required, bbb if not, | (ALPHA) |
| CC40-42 | REQEST(14) | - ERZ if radial/vertical strain $\varepsilon_{rx}$ is required, bbb if not, | (ALPHA) |
| CC43-45 | REQEST(15) | - ETZ if tangential/vertical strain $\varepsilon_{tz}$ is required, bbb if not, | (ALPHA) |
| CC46-48 | REQEST(16) | - UXb if total displacement in x-direction $U_x$ is required, bbb if not, | (ALPHA) |
| CC49-51 | REQEST(17) | - UYb if total displacement in y-direction $U_y$ is required, bbb if not, | (ALPHA) |
| CC52-54 | REQEST(18) | - SXX if xx-component of total stress $\sigma_{xx}$ is required, bbb if not, | (ALPHA) |
| CC55-57 | REQEST(19) | - SXY if xy-component of total stress $\sigma_{xy}$ is required, bbb if not, | (ALPHA) |
| CC58-60 | REQEST(20) | - SXZ if xz-component of total stress $\sigma_{xz}$ is required, bbb if not, | (ALPHA) |
| CC61-63 | REQEST(21) | - SYY if yy-component of total stress $\sigma_{yy}$ is required, bbb if not, | (ALPHA) |
| CC64-66 | REQEST(22) | - SYZ if yz-component of total stress $\sigma_{yz}$ is required, bbb if not, | (ALPHA) |
| CC67-69 | REQEST(23) | - EXX if xx-component of total strain $\varepsilon_{xx}$ is required, bbb if not, | (ALPHA) |

| | | | | |
|---|---|---|---|---|
| | CC70-72 | REQEST(24) | - EXY if xy-component of total strain $\varepsilon_{xy}$ is required, bbb if not, | (ALPHA) |
| | CC73-75 | REQEST(25) | - EXZ if xz-component of total strain $\varepsilon_{xz}$ is required, bbb if not, | (ALPHA) |
| | CC76-78 | REQEST(26) | - EYY if yy-component of total strain $\varepsilon_{yy}$ is required, bbb if not, | (ALPHA) |
| | CC79-80 | REQEST(27) | - EY if yz-component of total strain $\varepsilon_{yz}$ is required, bb if not. | (ALPHA) |
| | | | FORMAT (26A3,A2) | |
| 9) | CC 1- 2 | NPOS | - number of positions. | (INTEGER) |
| | | | FORMAT (I2) | |
| 10) | CC 1- 2 | LAYER(1) | - layer number of position 1, | (INTEGER) |
| | CC 3-14 | AX(1) | - abscissa of position 1 in units of length, | (REAL) |
| | CC15-26 | AY(1) | - ordinate of position 1 in units of length, | (REAL) |
| | CC27-38 | DEPTH(1) | - depth of position 1, in units of length, | (REAL) |
| | CC39-50 | [ETA(1)] | - optional; angle from which position 1 is observed with respect to the direction of the positive x-axis. ETA only needs to be given when the point of calculation is on the axis of one of horizontal surface loads, in degrees. For details, refer to reference 24. | (REAL) |
| | | | Note: Card 10 is repeated for each position. | |
| | | | FORMAT (I2,3E12.6, [E12.6]) | |

Cards 3-10 are repeated for each different system to be solved.

IBM FORTRAN Coding Form

GX28-7327-6 U/M 050**
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PROGRAM: INPUT FORMAT - SHELL BISAR
PROGRAMMER: | DATE: | PUNCHING INSTRUCTIONS: GRAPHIC / PUNCH | PAGE OF | CARD ELECTRO NUMBER*

STATEMENT NUMBER | CONT. | FORTRAN STATEMENT | IDENTIFICATION SEQUENCE

1 IDENTIFICATION | MONTH | DAY | YEAR | FORMAT(15A4,I2,I3,I5)

2 FORMAT(I2) # OF SYSTEMS TO BE SOLVED

3 FORMAT (I2,[I3]) # OF LAYERS, SMOOTH/ROUGH OPTION

4 E(I) | V(I) | THICK(I) | SLIP(I) | FORMAT(4E12.6) (ONE CARD PER LAYER I)

5 E(SUBGRADE) | V(SUBGRADE) | FORMAT (2E12.6)

6 FORMAT(I2) # OF LOADS

7 IDENT | LDSTRESS(J) | RADIUS(J) | X(J) | Y(J) | HOSTRESS(J) | PSI(J)
FORMAT (A4,2X,6E12.6) (ONE CARD PER LOAD J)

8 UR | UT | UZ | SRR | STT | SZZ | SRT | SRZ | STZ | ERR | ETT | EZZ | ERT | ERZ | ETZ | UX | UY | SXX | SXY | SXZ | SYY | SYZ | EXX | EXY | EXZ | EYY | EY
FORMAT(26A3,A2) REQUEST CARD FOR OUTPUT

9 FORMAT (I2) # OF POSITIONS FOR OUTPUT

10 LAYER(K) | X(K) | Y(K) | DEPTH(K) | ETA(K) | FORMAT (I2,3E12.6,[E12.6])
(ONE FOR EACH POSITION K)

*A standard card form, IBM electro 888157, is available for punching statements from this form

**Number of forms per pad may vary slightly

Figure A-3 Input Format - SHELL BISAR

ELSYM5

| | | | |
|---|---|---|---|
| 1) | CC 1- 5 | number of systems to be run. | (INTEGER) |
| | | FORMAT (I5) | |
| 2) | CC 1- 3 | punch the number 999, | (INTEGER) |
| | CC 5-60 | title to identify problem, | (ALPHA) |
| | | FORMAT (I3,A57) | |
| 3) | CC 1- 5 | number of elastic layers in the system, | (INTEGER) |
| | CC 6-10 | number of uniform circular loads to be applied normal to the surface of the system, | (INTEGER) |
| | CC11-15 | number of XY locations where results are desired, | (INTEGER) |
| | CC16-20 | number of Z locations where results are desired, | (INTEGER) |
| | | FORMAT (4I5) | |
| 4) | CC 1- 5 | layer number, | (INTEGER) |
| | CC 6-10 | thickness of layer in inches, | (REAL) |
| | CC11-15 | Poisson's ratio of layer, | (REAL) |
| | CC16-25 | modulus of elasticity for layer, in psi. | (REAL) |
| | | FORMAT (I5, 2F5.0,F10.0, 4X,[A2]) | |
| | | Note: One card for each elastic layer in the system, leave thickness blank for bottom elastic layer when layer is to be semi-infinite in thickness. If bottom elastic layer is resting on a rigid base, insert the thickness of the bottom elastic layer and CC30-31 (ALPHA) punch FF for full friction rigid base interface <u>or</u> CC30-31 (ALPHA) punch NF for no friction rigid base interface. Cards have to be in sequence from top to bottom elastic layer. | |
| 5) | CC 1-10 | load force in pounds, | (REAL) |
| | CC11-20 | load pressure in pounds per square inch, | (REAL) |
| | CC21-30 | load radius in inches. | (REAL) |
| | | Note: Any two of the above items can be input, program determines the third. Only one card required. | |
| | | FORMAT (3F10.0) | |

| | | | |
|---|---|---|---|
| 6) | CC 1-10 | X position of a load, | (REAL) |
| | CC11-20 | Y position of a load. | (REAL) |
| | | Note: One card per load. | |
| | | FORMAT (2F10.0) | |
| 7) | CC 1-10 | X position for evaluation, | (REAL) |
| | CC11-20 | Y position for evaluation. | (REAL) |
| | | Note: One card for each XY position for evaluation. | |
| | | FORMAT (2 F10.0) | |
| 8) | CC 1- 5 | first Z value for evaluation, | (REAL) |
| | CC 6-10 | second Z value for evaluation, | (REAL) |
| | CC11-15 | third Z value for evaluation, etc. | (REAL) |
| | | Note: Only one card required, maximum of ten values on the card. | |
| | | FORMAT (10F5.0) | |

Cards 2-8 are repeated for each different system to be solved.

GX28-7327-6 U/M 050**
Printed in U.S.A.

**IBM** FORTRAN Coding Form

PROGRAM INPUT FORMAT - ELSYM5

PROGRAMMER | DATE | PUNCHING INSTRUCTIONS | GRAPHIC | PUNCH | PAGE OF | CARD ELECTRO NUMBER*

| C (cols. 1–5) | CONT. (col. 6) | FORTRAN STATEMENT (cols. 7–72) | IDENTIFICATION SEQUENCE (cols. 73–80) |
|---|---|---|---|
| 1 | | FORMAT (I5) #SYSTEMS TO BE SOLVED | |
| 2 999 | | IDENTIFICATION FORMAT(I3, A57) | |
| 3 | | FORMAT (4I5) #LAYERS, #LOADS, # OF XY LOCATIONS WHERE RESULTS DESIRED, # OF Z LOCATIONS WHERE RESULTS DESIRED | |
| 4 J | | H(J) V(J) E(J) FORMAT (I5, 2F5.0, F10.0) (ONE CARD PER LAYER J) | |
| 5 LOAD | | PRESSURE RADIUS FORMAT (3F10.0) (INPUT ANY TWO) | |
| 6 X(J) | | Y(J) FORMAT (2F10.0) (ONE CARD PER LOAD J) | |
| 7 X(I) | | Y(I) FORMAT (2F10.0) (ONE CARD PER POINT OF INTEREST I) | |
| 8 Z(1) | | Z(2) Z(3) ... FORMAT (10F5.0) | |

*A standard card form, IBM electro 888157, is available for punching statements from this form

**Number of forms per pad may vary slightly

Figure A-4 Input Format - ELSYM5

PSAD2A - Input Cards

| | | | |
|---|---|---|---|
| 1) | CC 1- 5 | number of systems to be run. | (INTEGER) |
| | | FORMAT (I5) | |
| 2) | CC 1-80 | any combination of alphameric characters may be used to identify the problem to be solved. | (ALPHA) |
| | | FORMAT (A80) | |
| 3) | CC 1-10 | total load in pounds, | (REAL) |
| | CC11-20 | load stress in psi, | (REAL) |
| | CC21-30 | load radius in inches, | (REAL) |
| | | Note: Any two of the above items can be input, program determines the third. | |
| | CC31-40 | distance between loads in terms of number of load radii, must be greater than or equal to zero and less than or equal to two, | (REAL) |
| | CC41-45 | number of points to be read in for describing the curve of resilient modulus vs repeated vertical stress for subgrade layer. (see cards 5 and 6) | (INTEGER) |
| | | FORMAT (4F10.0,I5) | |
| 4) | CC 1-10 | initially assumed modulus of elasticity (psi) for layer 1 (top layer), | (REAL) |
| | CC11-20 | Poisson's ratio for layer 1, | (REAL) |
| | CC21-30 | coefficient $\bar{k}$ in the relationship $M_R=\bar{k}\theta^{\bar{n}}$ for layer 1. If layer is linearly elastic then $M_R=\bar{k}$, | (REAL) |
| | CC31-40 | coefficient $\bar{n}$ in the relationship $M_R=\bar{k}\theta^{\bar{n}}$ for layer 1. If layer is linearly elastic then $\bar{n}$ is zero, | (REAL) |
| | CC41-50 | unit weight of material in layer 1 in pounds per cubic foot, | (REAL) |
| | CC51-60 | thickness of layer 1 in inches. | (REAL) |
| | | FORMAT (6F10.0) | |
| | | Note: One card per layer, a total of four of the above cards required for the top four layers (subgrade card follows). | |

| | | | |
|---|---|---|---|
| 5) | CC 1-10 | initially assumed modulus of elasticity (psi) for layer 5, | (REAL) |
| | CC11-20 | Poisson's ratio for layer 5. | (REAL) |
| | | FORMAT (2F10.0) | |
| 6) | CC 1-10 | deviator stress (psi) for the first point, must equal zero, | (REAL) |
| | CC11-20 | resilient modulus (psi) corresponding to the first deviator stress point, | (REAL) |
| | CC21-30 | deviator stress (psi) for the second point, | (REAL) |
| | CC31-40 | resilient modulus (psi) corresponding to the second deviator stress point, etc. | (REAL) |
| | | Note: A maximum of four points per card (eight values) and a maximum of five cards (twenty points total). | |
| | | FORMAT (8F10.0) | |

Cards 2-6 are repeated for each different system to be solved.

**IBM** FORTRAN Coding Form

GX28-7327-6 U/M 050**
Printed in U.S.A.

| | |
|---|---|
| PROGRAM | INPUT FORMAT - PSAD2A |
| PROGRAMMER | |
| DATE | |
| PUNCHING INSTRUCTIONS | GRAPHIC / PUNCH |
| PAGE OF | |
| CARD ELECTRO NUMBER* | |

| Card | FORTRAN STATEMENT | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | FORMAT(I5) #SYSTEMS TO BE SOLVED | | | | | | |
| 2 | IDENTIFICATION | | | | | | FORMAT(A8Ø) |
| 3 | LOAD | PRESSURE | RADIUS | DISTANCE | #POINTS | FORMAT(4F1Ø.Ø,I5) | |
| | ← INPUT ANY TWO → | | | | | | |
| 4 | E(J) | V(J) | $K_1$(J) | $K_2$(J) | DENSITY(J) | H(J) | FORMAT(6F1Ø.Ø) |
| | | | | | | (ONE CARD FOR EACH OF 4 TOP LAYERS - J) | |
| 5 | E(5) | V(5) | FORMAT(2F1Ø.Ø) | | | | |
| 6 | $\sigma_z$(1) | $M_R$(1) | ... | ... | FORMAT(8F1Ø.Ø) | | |

*A standard card form, IBM electro 888157, is available for punching statements from this form

**Number of forms per pad may vary slightly

Figure A-5 Input Format - PSAD2A

# APPENDIX B

## TYPICAL RESILIENT MODULUS VALUES

## MATERIAL PROPERTIES

Introduction:

Utilization of the computer programs described in this report requires input data which describe the resilient modulus and Poisson's ratio for each pavement layer. Modulus values are obtained most desirably from laboratory or field measurements made on the material in question. A less desirable, but nevertheless useful, approach to many engineering problems involves the estimation of modulus based on literature data.

This report section is intended to provide the engineer with a "feel" for elasticity modulus values and aid in estimating modulus when actual measurements are not available. As of this writing, data concerning Alaskan materials is badly needed. Some information has been gained from Interior Alaska highways where soil layer moduli were derived from Falling Weight Deflectometer readings. Laboratory testing has also been done on a random sampling of about a dozen asphalt cores taken from the Fairbanks area. These were made with AC 2.5 and 200-300 penetration grade asphalt cements and represent the softest paving products used within the State. No attempts have been made to measure Poisson's ratio on Alaskan materials. Most of the following data was derived from general literature sources as noted.

Information is presented in the following order:

° Data on Alaskan Materials
  - asphalt concrete
  - unbound soil materials

° Literature Data
  - calculation of resilient modulus for asphaltic concrete
  - unbound soil materials

## Alaskan Materials:

Table 1 summarizes results of resilient modulus tests on asphalt concrete cores obtained near Fairbanks. These data represent the softest of Alaskan paving materials and are obtained from an area (Interior Alaska) which minimizes asphalt aging.

TABLE 1

Resilient Modulus Properties of Alaskan Asphalt Concrete

general properties:
- asphalt content = 5% - 6%
- air voids = 2% - 4%
- pavement age = 2 - 10 years

test method:
- 200, $\mu\varepsilon$
- 0.1 sec load pulse
- 1.0 sec load interval

| Temperature (°F) | Resilient Modulus (PSI) Minimum (New) | Maximum (Aged) |
|---|---|---|
| 70 | 36,000 | 410,000 |
| 60 | 110,000 | 620,000 |
| 50 | 220,000 | 920,000 |
| 40 | 400,000 | 1,300,000 |
| 30 | 610,000 | 1,700,000 |
| 20 | 980,000 | 2,200,000 |
| 70* | 74,100 | 82,900 |
| 70** | 58,100 | 98,600 |

* recycled mix with AC 2.5 as additive (laboratory sample)
** recycled mix with AC 1.75 as additive (laboratory sample)

Resilient modulus values for Interior Alaska soils were calculated from Falling Weight Deflectometer data. These were determined through a "back-calculation" of deflection basin shape based on known layer thicknesses and reiterative estimate of soil moduli. Soil moduli used during the final (basin-matching) iteration were assumed to provide a valid indication of in situ conditions during the spring thaw when field testing was done. Figure 1 shows the relationship between soil fines and calculated resilient modulus, based on the Falling Weight Deflectometer data. These plots, especially in the case of base/subbase materials, may extend to modulus values which are too high. A maximum modulus of 80,000 psi is therefore suggested for base or subbase gravels which are placed within the upper 24 inches of the road structure. Any soils located below 24 inches in depth should be assumed as subgrade and the right side of Figure 1 should be used to estimate modulus.

In computer programs such as CHEV5L with iteration and PSAD2A, the non-linearity, i.e. stress dependency of the soil layers, must be input. As of this writing only five samples of Alaskan materials have been tested through the range of load conditions required for derivation of "stress sensitivity" equations. Table 2 contains the stress sensitivity equations derived from these data.

TABLE 2

Stress Sensitivity Equations for Common Interior Alaska Soils

Fox Silt

| | |
|---|---|
| $M_R = 4{,}073\sigma_d^{0.235}$ | $R^2 = 0.37$ |
| $M_R = 2{,}184\theta^{0.349}$ | $R^2 = 0.71$ |
| $M_R = 3{,}566\sigma_3^{0.366}$ | $R^2 = 0.83$ |

Fairbanks Sand and Gravel C-1

| | |
|---|---|
| $M_R = 16{,}010\sigma_d^{0.400}$ | $R^2 = 0.83$ |
| $M_R = 10{,}499\theta^{0.410}$ | $R^2 = 0.90$ |
| $M_R = 16{,}284\sigma_3^{0.500}$ | $R^2 = 0.98$ |

Palmer Base D-1

| | |
|---|---|
| $M_R = 7{,}110\sigma_d^{0.589}$ | $R^2 = 0.76$ |
| $M_R = 3{,}481\theta^{0.614}$ | $R^2 = 0.69$ |
| $M_R = 9{,}969\sigma_3^{0.562}$ | $R^2 = 0.60$ |

Palmer Subbase

| | |
|---|---|
| $M_R = 11{,}305\sigma_d^{0.467}$ | $R^2 = 0.85$ |
| $M_R = 5{,}052\theta^{0.558}$ | $R^2 = 0.97$ |
| $M_R = 11{,}889\sigma_3^{0.562}$ | $R^2 = 0.95$ |

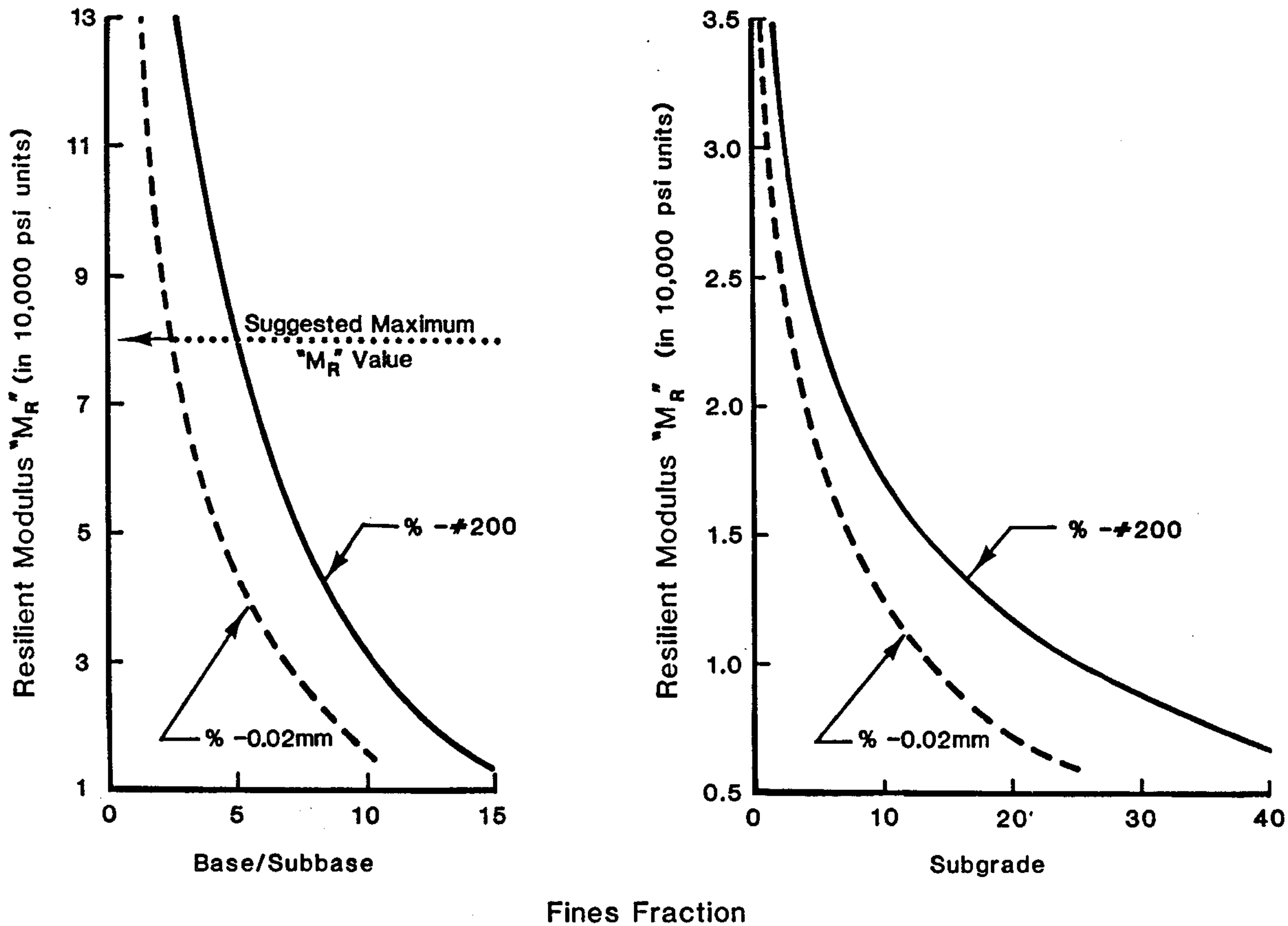



Figure 1: Fines Content versus Resilient Modulus for Alaskan Soils

Fairbanks Sand and Gravel D-1

$$M_R = 7{,}914\sigma_d^{0.563} \qquad R^2 = 0.84$$

$$M_R = 3{,}039\theta^{0.669} \qquad R^2 = 0.94$$

$$M_R = 8{,}551\sigma_3^{0.670} \qquad R^2 = 0.91$$

Where:

$M_R$ = Resilient modulus (PSI)

$\theta$ = Bulk stress (sum of principle stresses $\sigma_1 + 2\sigma_3$)

$\sigma_d$ = Deviator stress

$\sigma_3$ = Confining pressure used in triaxial test chamber

Literature Information:

General:

Although literature sources often indicate a single modulus value for a particular material type, elasticity is actually variable and dependent on state of stress.

Testing variables which control the elastic properties of various road construction materials were indicated by Hicks (1) and are presented below:

TABLE 3

Most Important Variable

| Material | Primary Variable | Secondary Variable |
|---|---|---|
| Asphalt Concrete | temperature, rate of loading | confining pressure, deviator stress |
| Granular Base | confining pressure | deviator stress |
| Cement Stabilized Base | test method (bending or compression) | confining stress |
| Final Grained Soil | deviator stress | confining stress |

It is sometimes possible to simulate stress dependency in a single material type by subdividing it into layers and assuming a stress condition at each mid-layer depth.

Poisson's ratio is the ratio of lateral strain to load-axis strain. It is a measurable characteristic of various material types and is a necessary input for the computer programs discussed in this paper. The following ratios are suggested for use by Alaska Department of Transportation and Public Facilities (DOTPF) engineers if laboratory test data are not available:

| | |
|---|---|
| Asphalt Concrete | 0.35 |
| Granular Base | 0.45 |
| Subgrade | 0.45 |

Poisson's ratios are not significantly effected by most changes in a material's in situ stress regime. The ratio value for asphalt concrete however, has somewhat of a direct but non-linear temperature dependency, i.e. the Poisson ratio increases with increasing temperature (2).

Asphalt Concrete:

Calculation of asphalt concrete resilient modulus is a four step process developed by Norman McLeod and from the original work of Van der Poel (3). The necessary steps, in order, are:

1) calculation of a penetration - viscosity number (PVN),
2) estimation of base temperature (nomograph solution),
3) estimation of <u>asphalt cement</u> modulus (nomograph solution, and
4) calculation of <u>asphalt concrete</u> modulus.

° PVN is calculated from the equation:

$$PVN = [(L - X)/(L - M)]\ (-1.5)$$

where:

$X$ = log of kinematic viscosity (centistokes) for the asphalt
$L = 4.25800 - 0.79674$ (log pen @ 77°F)
$M = 3.46289 - 0.61094$ (log pen @ 77°F)

- Base temperature is estimated from Figure 2 as indicated in the figure example.

- Asphalt cement modulus is estimated from Figure 3 as indicated in the figure example.

- Asphalt concrete modulus is calculated by means of the following equation:

$$S_m = S_b \left[1 + (2.5/n)(C_V/(1-C_v))\right]^n$$

where:

$S_m$ = mix modulus (kg/cm²)
$S_b$ = asphalt cement modulus (kg/cm²)
$n = 0.83 \log (4 \times 10^5/S_b)$
$C_V$ = volume of aggregate/(total volume of solids)

In order to convert the final modulus value into English units (psi), $S_m$ is multiplied by 14.23. The preceding equation is reasonably accurate for mix air void contents of about 3 percent. A 3 percent air void content would correspond well with most Alaskan pavements although a correction factor for higher voids is indicated in Yoder and Witczak (2).

Soil Materials:

Soil modulus values presented in this section are generalized indications of material type and expected values. Table 4 relates gross soil classification (AASHTO and Unified) to resilient modulus (3). Suggested use of this table is for making rough estimates and checking the reasonableness of assumed or calculated values. Similarly, Table 5 provides a "handle" on

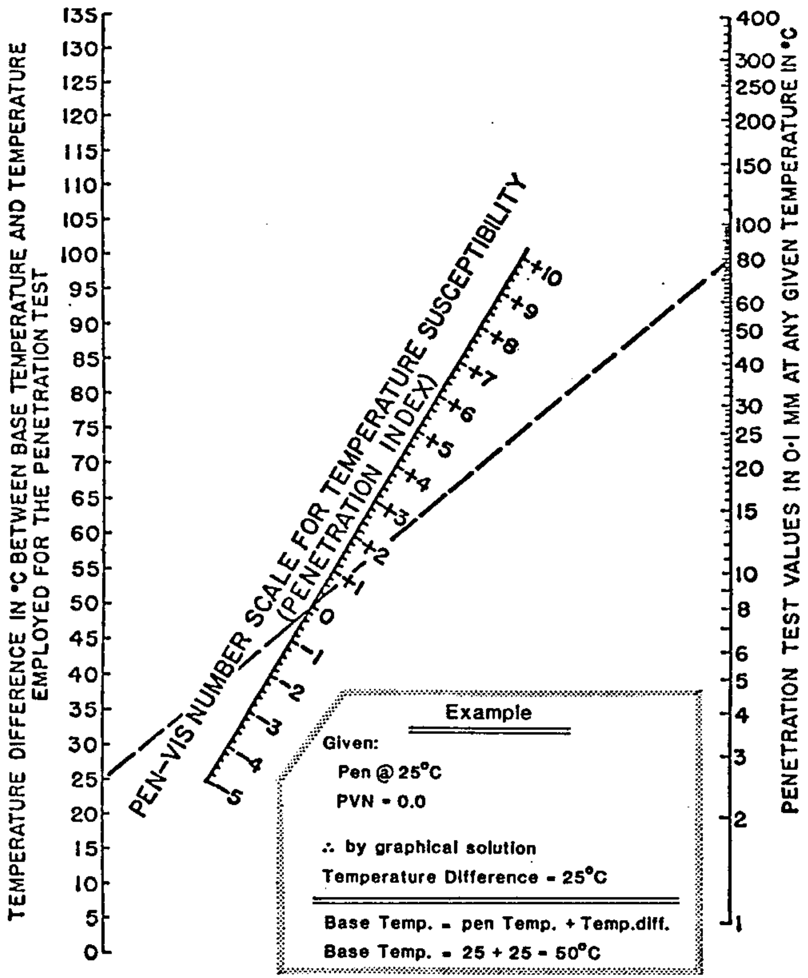



Figure 2: Relationship between penetration, Pen-Vis number, and base temperature.

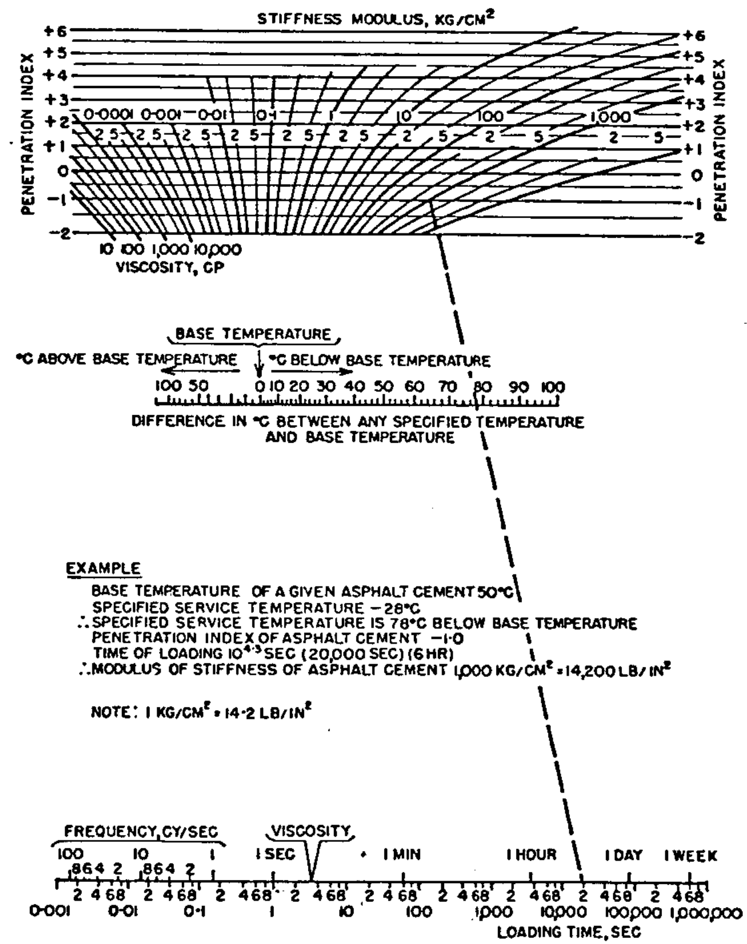
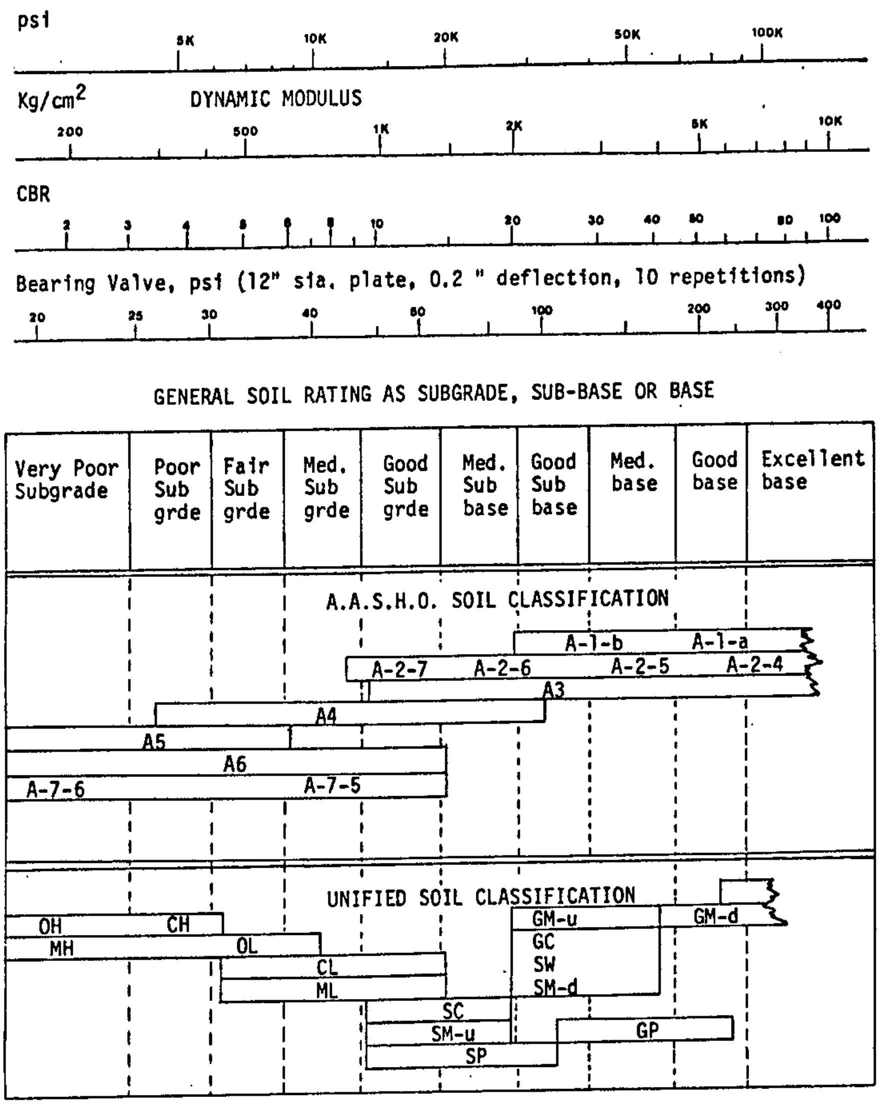



Figure 3: McLeod's suggested modification of Heukelom and Klomp's version of van der Poel's nomograph for determining modulus of stiffness of asphalt cements. (Reference 1)

Table 4. CRUDE EMPERICAL RELATIONSHIPS BETWEEN RESILIENT MODULUS AND OTHER TEST DATA




from: G. Hicks, reference 3

TABLE 5: SELECTED MEASURED DYNAMIC MODULI FOR PAVEMENT MATERIAL

| Unbound Granular Base | Frequency & Duration | Load Repetition | Dynamic Modulus |
|---|---|---|---|
| Colorado; standard Base, ½" max and 8.7% < No. 200; standard subbase, 2½" max and 7.9% < No. 200 | 120 cpm, 0.2 sec | 10,000 | $10{,}618\sigma_3^{.447}$, 2.4% w-c<br>$10{,}019\sigma_3^{.465}$, 6.3% w-c<br>$8{,}687\sigma_3^{.496}$, 8.2% w-c |
| California; well-graded and subrounded gravel 3/4" max; class 2 aggregate base | 30 cpm, 0.1 sec | 100 | Dry<br>10,000 to 13,000 psi, 3% < No. 200, $\sigma_3^{.53}$<br>8,000 to 9,000 psi, 8% < No. 200, $\sigma_3^{.59}$<br>Partially saturated<br>7,000 to 10,000 psi, 3% < No. 200, $\sigma_3^{.55}$<br>5,000 to 7,000 psi, 8% < No. 200, $\sigma_3^{.60}$ |
| California; well-graded and angular crushed stone 3/4" max; class 2 aggregate base | 30 cpm, 0.1 sec | 100 | Dry<br>11,000 to 12,000 psi, 3% < No. 200, $\sigma_3^{.57}$<br>14,000 to 15,000 psi, 10% < No. 200, $\sigma_3^{.50}$<br>Partially saturated<br>9,000 to 10,000 psi, 3% < No. 200, $\sigma_3^{.57}$<br>7,500 to 9,500 psi, 10% < No. 200, $\sigma_3^{.57}$ |
| Soil-aggregate of 17% silty sand and 83% crushed granite; 100% T-180; w-c = 5.1% | 33 cpm, 0.1 sec | 10,000 | $3{,}836\theta^{.53}$<br>$3{,}145\theta^{.55}$ |
| California; well-graded and subrounded gravel 3/4" max; class 2 aggregate base (dry) | 30 cpm, 0.2 sec | 10,000 | $7{,}000\sigma_3^{.55}$ |
| Silty fine sand 100% AASHO T-99; 40% < No. 200 w-c = 13.4% | 33 cpm, 0.1 sec | 10,000 | $1{,}856\theta^{.81}$<br>$3{,}126\theta^{.37}$ |
| **Subgrade** | | | |
| AASHO class A-6 silty clay; w-c = 14 to 18 percent; $\gamma_d$ = 110 to 114 pcf | 120 cpm, 0.2 sec | 10,000 | 3,000 to 4,000 psi, 18% w-c<br>7,000 to 8,000 psi, 16% w-c<br>15,000 to 20,000 psi, 14% w-c |
| Micaceous silty sand subgrade | 33 cpm, 0.1 sec | 10,000 | 3,000 to 4,000 psi, wet season<br>1,500 to 2,000 psi, dry season |
| Silty clay (AASHO Test); $\sigma_d$ = 5 to 10 psi; $\sigma_3$ < 3 psi; $\gamma_d$ = 110 to 115 pcf | 20 cpm, 0.25 sec | | 13,000 psi, 13% w-c<br>10,000 psi, 14% w-c<br>8,000 psi, 15% w-c<br>7,000 psi, 16% w-c<br>2,000 to 5,000 psi, 17% w-c<br>2,000 psi, 18% w-c |
| Highly plastic clay (PI = 36.5) and silty clay (PI = 25.5) | 30 cpm, 0.1 sec | 10,000 | $4{,}150\sigma_d^{1.0}$<br>$3{,}200\sigma_d^{5.2}$ |
| AASHO class A-7-6 silty clay; w-c = 11 to 20% $\gamma_d$ = 102 to 105 pcf | 120 cpm, 0.2 sec | 10,000 | 7,000 to 10,000 psi, 20% w-c<br>15,000 to 16,000 psi, 18% w-c<br>14,000 to 15,000 psi, 16% w-c |
| AASHO class A-6 to A-7-6 silty clay | 30 cpm, 0.1 sec | 100 | 10,000 psi, 1 atm (soil moisture suction during test)<br>100,000 psi, 10 atm |

from: G. Hicks, Reference 3

estimating non-linear modulus characteristics of various granular soil types.

In the main-body text of this report (pp. 13-19), Dr. Hicks has shown the effects of variations in stress and environment on cemented and non-cemented materials. Notably, he has indicated that curing time very significantly effects the stiffness of emulsion treated aggregates. In Hicks' example, approximately a 20-fold increase in modulus occurs within a 8-year period.

Summary:

This Appendix is suggested as an aid to developing reasonable input moduli for the computer programs discussed in this report and evaluating data which results from field or laboratory tests. Typical resilient modulus values have been presented for both asphalt concrete and soil materials. Information was extracted from limited Alaska DOTPF testing and literature sources. These data are provided so that users of programs presented within this report will have some feeling for elastic properties of common highway construction materials. Effects of stress state temperature and aging on resilient modulus have been indicated.

When possible, the engineer should utilize actual measured resilient moduli as program input rather than rule of thumb or assumed values.

References:

1. Hicks, G., "Improved Pavement Design Methods," Lecture Notes for Alaska DOTPF Seminar, Anchorage, Alaska, 1981.

2. Yoder and Witczak, "Principals of Pavement Design," 2nd ed., Wiley, 1975.

3. Transportation Research Board, "Relationship of Asphalt Cement Properties to Pavement Durability," NCHRP Synthesis of Highway Practice 59, Washington, D.C., 1979.

# APPENDIX C

## Operation of Computer Programs on the Boeing System

Availability: The five computer programs discussed within the main body of this report are available for general DOTPF use on the Boeing Computer System (BCS). Their application is encouraged by engineers involved in the planning, design, or structural evaluation of asphalt concrete pavements. This Appendix will provide the first-time BCS user with information necessary to run the described programs as well as create and modify input data files.

Each program is accompanied by a procedure ("proc") file which controls its execution and an example data file for testing purposes. It is suggested that new users familiarize themselves with the BCS by making some trial runs utilizing the available sample data.

The instructional content of this Appendix is directed to the following subject areas:

- ° general sign-on/sign-off procedures used on BCS
- ° running selected computer programs
    - transfer of files from tape storage to on-line storage
    - test data/new data
    - run commands
- ° text editing
    - modification of sample data
    - creation of new data files

Most DOTPF personnel who have previously used BCS have operated highway earthwork and geometrics programs within the BCS-TSO subsystem. However, all programs mentioned in this report are available only within the BCS-EKS subsystem. The EKS subsystem is related to TSO as shown in diagram below:

FIGURE 1

```
                              MAINSTREAM
                              BCS NETWORK
                                   !
      -------------------------------------------------------------
      !                            !                              !
      !                            !                              !
  M/EKS-VSP                      M/CTS                          M/TSO
     CDC                          IBM                            IBM
 CYBER 760's                    3033's                         3033's
   CRAY-1S
    BATCH                   CONVERSATIONAL                      BATCH
 INTERACTIVE                                                 INTERACTIVE
                                                             PROGRAMMER
                                                            PRODUCTIVITY

 BELLEVUE, WA                 VIENNA, VA                     VIENNA, VA
```

For the benefit of those who will be utilizing both TSO and EKS subsystems, the following section taken from Boeing's manual "MAINSTREAM-EKS Introduction" will be of interest.

> "BCS provides commercial customers access to two large data centers. One in Bellevue, Washington on the West Coast; the other

in Vienna, Virginia on the East Coast. Each Data Center carries a full compliment of capabilities and services (virtually limitless for the average user). The Bellevue Data Center (MAINSTREAM EKS-VSP) is comprised of Control Data Corporation and CRAY Research Institute mainframes and is ideally suited for scientific/engineering computing. The Vienna Data Center (MAINSTREAM CTS and MAINSTREAM TSO) is IBM mainframes and suited for large and small database and information management processing (TSO) and interactive conversational processing (CTS). (See Figure 1).

The actual access to the BCS Network is accomplished with a terminal and a dial up phone/modem configuration. Within the State of Alaska service is provided by dialing a local Anchorage phone number or the DNA (800) phone number. Selection of a specific data center is via a logon process with BCS validated userid's and passwords. BCS will set up these userid's as a customer desires access. Use of the userid/password is the responsibility of the customer, once BCS installs it and turns control over to the user.

Although the exact logon procedure for each of the 3 systems is slightly different, the function is the same and through utilization of procedures access to specific applications is simplified. Each system has its own on-line editor, again all are slightly different in syntax, however close enough to make learning one after utilization of another relatively easy."

<u>Sign On - Sign Off</u>: This section describes procedures involving the telephone "modem" which are necessary to connect the computer user with EKS. The sequence of user operations is presented in an outline format to simulate prompting and response interaction occurring at the terminal.

Terminal power switch -- on
Modem configuration:
  HS switch -- towards "HS" (up position)
  DA-VO-MA switch -- on "VO" position
Dial telephone:
  e.g., in Fairbanks dial 101-800-426-1260
  wait for tone
  switch DA-VO-MA to "DA" position
  hang up telephone

Note: This dial-up example is based on the use of Racal-Vadic modem. Other units will vary slightly in operation.

On computer terminal:
  press <CR> (Note: CR = carriage return)

The Boeing computer system should now be on-line and an introductory "sign-on" banner should appear on the terminal screen.

The sign-on prompt/<response> sequence then continues as in the following example:
  USER NUMBER: <#>
  PASSWORD: <password>
  TERMINAL 347 TTY

RECOVER/USERID: <reference name>

The user is now signed onto BCS and the terminal will prompt either:
C> or N>

If the prompt "N>" appears, the user should respond with "BATCH" as follows:
N>BATCH

A "C>" prompt should appear. The user is now at a basic command level and ready for program operation.

When finished with a session at the computer terminal, the user will type "BYE" in response to the "C>" prompt.

C> BYE

Running Programs: Each "program" exists on magnetic tape storage as a series of three (3) data files:

1) the program itself, which has been transformed into a compiled format,
2) the job process ("proc") file which controls operation of the above program and,
3) an example data file which can be used to test run the program.

The first step in program operation is to transfer the desired magnetic files onto disk file storage. This is done by a simple 2-command sequence which simultaneously places all 3 of the above file types for any selected program into permanent disk storage. Table 1 lists the magnetic tape files which pertain to each pavement analysis program.

Table 1

Identification of Mechanistic Program Files on Magnetic Tape

| Program Type | Compiled Program | Proc. | Test Data |
|---|---|---|---|
| CHEV5L | OCHEV5L | PCHEV5L | DCHEV5L |
| CHEV5L w/ iteration | OCHEV5LW | PCHEV5LW | DCHEV5LW |
| BISAR | OBISAR | PBISAR | DBISAR |
| ELSYM5 | OELSYM5 | PELSYM5 | DELSYM5 |
| PSAD2A | OPSAD | PPSAD | DPSAD |

Files are transferred from tape to the user's permanent disk by using a proc command file. Tape to disk proc command files are referenced by name to their respective programs. They are:
GCHEV5L

GCHEV5LW
GBISAR
GELSYM5
GPSAD

Tape to disk transfer is done as in the following example command sequence:

C>GET GBISAR/UN=YFAIØ1
C>SUBMIT,<job name>,NL

It is the second command which actually initiates the transfer activity. After the second command is given the user should periodically check to see if the tape to disk transfer has been successfully completed. A seven digit job identification number will appear at the user's terminal after the second command is given. A job status check is done using this ID number, with the command:

C>FIND,<job ID #>

The user should be aware that it may take up to a few hours for the tape to disk transfer to take place. Also, the "FIND" command will prompt recognition of a job only during the time when it is actually being processed. For example, the user may not be able to get a job status report if the "FIND" command is used too soon after the tape to disk job has been submitted. Likewise, if the job has been completed, the "FIND" command will result in no response.

Another way of checking status of the tape to disk transfer is to simply see if the requested files have been loaded into the disk files. This is done with the command:

C>CATLIST

The names of all of the user's permanent files will be printed in response to the "CATLIST" command.

Once all selected files reside in the user's permanent disk storage, program runs can be made as in the subsequent example.

C>CALL, PCHEV5L (DATA = DCHEV5L, OUT = OUTFILE)

In this example case, the proc (PCHEV5L) causes the program (OCHEV5L) to run using an example data file (DCHEV5L) as input data. Output from the run is placed into the disk file (OUTFILE). At the user's discretion, the output file (OUTFILE) can either be saved for future examination or immediately printed at the user's terminal site.

Printing Output: When the computer program run is made the results are directed into an EKS permanent disk file (OUTFILE) which is named in the user's run command, e.g., C>CALL, PCHEV5L (DATA = DCHEV5L, OUT = OUTFILE). Before contents of the permanent file can be listed, they must first be brought into local file space by the command:

C>GET, OUTFILE

where:

"OUTFILE" is the designated name of the program output permanent disk file. All filenames must be 7 or less letters long. The words INPUT and OUTPUT are reserved by the computer system and cannot be used.

After the file has been brought into local "space" it can be printed with the command:

C>LIST, FN = OUTFILE

If the user desires to list the output file more than once, it is necessary to use the following command between listings:

C>REWIND, OUTFILE

The Edit Subsystem - Building and Editing Data Files: Data files can be constructed and/or modified using the EKS editor subsystem.

To modify an existing permanent disk file, it is first brought into local file space with the command:

C>GET, OUTFILE

The editor is then entered with:

C>CME, OUTFILE

The file "OUTFILE" is now ready for modification through use of edit subsystem commands which will be presented within the following text.

If a new data file is to be constructed, the user types the command:

C>CME, NEWFILE

where:

"NEWFILE" is a permanent disk file name which has not been brought into local file space by the "GET" command, or is a previously unused file name.

After entering the previous command, the user is in the edit subsystem and the terminal will prompt with:

I>

This indicates that the user is in the "build" mode and that text may be entered in the desired format. When text input is completed, the carriage return is depressed on a blank line and the editor will respond by switching from a text building to a command mode. The command mode prompt is:

E>

While in this mode a series of command statements can be used to manipulate, i.e., print, modify, delete, etc., the file.

The reader should note that the first line of any file being edited is always null (blank). This blank "header line" allows for the insertion of text at the beginning of the file.

Some basic edit subsystem commands are:

| | |
|---|---|
| E>TOP | Returns line "pointer" to top of file; |
| E>BOTTOM | Moves pointer to bottom of file; |
| E>NEXT | Moves pointer to next line; |
| E>NEXT N | Moves pointer N lines forward; |
| E>UP N | Moves pointer N lines backward; |
| E>DELETE | Deletes current line; |
| E>DELETE N | Deletes current plus following N-1 lines; |
| E>PRINT | Prints current line; |
| E>PRINT N | Prints current line plus following N-1 lines; |
| E>PRINT * | Prints current line plus all lines to end of file; |
| E>LOCATE/<string>/ | Locates file line where the desired "string" first appears; (Note: When locating a string the pointer will normally move only forward in the file. However, a negative sign placed before the locate command will cause the pointer to move upward through the file during its search.) |
| E>CHANGE/<string A>/<string B>/ | Locates and replaces "string A" with "string B"; |
| E>REPLACE<#> | Replaces one or more lines of the data file -- it is followed by a >I prompt; |
| E>INSERT | Allows insertion of lines of text into the data file -- an I> response will result from this command. When insertion is completed, a carriage return on a blank line will return the user to the edit command (E>) mode. |

Storage of a new or modified file is done in the following way:

E>FILE,<filename>

The file, <filename>, which is used in this command need not (necessarily) exist prior to the command. If the file already exists, its contents will be replaced by those of the newly saved file.

When the computer session is completed, unwanted files should be released to avoid unnecessary disk space rental charges. The command used for removing a specific file is:

C>PURGE,<filename>

## SUGGESTED REFERENCES

| | |
|---|---|
| MAINSTREAM-EKS Reference Guide | 10208-002 |
| MAINSTREAM-EKS Interactive Timesharing (KIT) Users Manual | 10208-005 |
| MAINSTREAM-EKS Introduction | 10208-130 |
| MAINSTREAM-EKS Facilities and Services | 10208-131 |
| MAINSTREAM-EKS Control Statement Manual | 10208-133 |